HYDROLOGY OF THE LEEWARD AQUIFERS,

SOUTHEAST OAHU, HAWAII

By Paul Eyre, Charles Ewart, and Patricia Shade

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DONALD PAUL HODEL, Secretary

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Dallas L. Peck, Director

For additional information write to:

District Chief
U.S. Geological Survey, WRD
Rm. 6110, 300 Ala Moana Blvd.
Honolulu, Hawaii 96850

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CONVERSION TABLE

The following table may be used to convert measurements in the inch-pound system to the International System of Units (SI).

Multiply	By	To obtain
	Length	
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile, statute (mi)	1.609	kilometer (km)
	Area	
square foot (ft^2)	0.0929	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
cubic foot (ft^3)	0.02832	cubic meter (m^3)
gallon (gal)	3.785	liter (L)
million gallons (10^6 gal or Mgal)	3,785	cubic meters (m^3)
	Volume Per Unit Time (includes Flow)	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per second-day (ft^3/s-d)	2,447	cubic meter (m^3)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
million gallons per day (10^6 gal/d or Mgal/d)	0.04381	cubic meter per second (m^3/s)
	Miscellaneous	
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)
foot per day (ft/d)	0.3048	meter per day (m/d)
foot squared per day (ft^2/d)	0.0929	meter squared per day (m^2/d)
micromho per centimeter at 25° Celsius (µmho/cm at 25°C).	1.000	microsiemens per centimeter at 25° Celsius (µS/cm at 25°C).

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ABSTRACT

The leeward southeast Oahu ground-water area includes the Waialae and Wailupe-Hawaii Kai aquifers. The Waialae aquifer is separated from the ground water of Kaimuki to the west by Palolo valley fill and the Kaau rift zone, and from the Wailupe-Hawaii Kai aquifer to the east by a line of northeast-trending volcanic dikes. The distinct ground-water head changes across these boundaries indicate that the aquifers are separate, with little or no leakage between them.

A water budget of leeward southeast Oahu determined the quantity and spatial distribution of ground-water recharge. These estimates of recharge, 6 million gallons per day over the Waialae area and 9.1 million gallons per day over the Wailupe-Hawaii Kai area, were used as input to a finite-element two-dimensional ground-water flow model. Ground-water heads were simulated in the modeled aquifer for several pumping scenarios. Projected pumpage from the recently drilled wells in the area is predicted to draw the water table down about one foot from its present mean position.

The existing ground-water development of 1.4 million gallons per day is small compared to the quantity of ground-water that flows through the area and discharges to the sea. Because the Waialae and Wailupe-Hawaii Kai aquifers are isolated from adjacent ground-water bodies, they can be fully developed without affecting ground-water resources outside the area.

INTRODUCTION

Many areas of the United States are dependent on ground water for a large part of their total water needs or for a ready reserve supply during droughts. As part of the national response to the severe drought of 1976-77 in the continental United States, the 95th Congress introduced a national program for the analysis of regional aquifer systems. The U.S. Geological Survey is conducting these studies.

Approximately 30 regional aquifer systems have been identified nationwide including the island of Oahu, Hawaii. The Regional Aquifer System Analysis (RASA) study for Oahu has two principal objectives: (1) to provide a firm understanding of the complex hydrology and hydraulics of Oahu's ground-water system, and (2) to provide a framework for future hydrologic studies and data gathering.

Oahu's regional aquifer system can be divided into five study areas which are enclosed by topographic divides (fig. 1). For the determination of recharge to the underlying ground-water bodies, topographic divides serve well as study area boundaries even though surface- and ground-water divides may not coincide. Discrepancies between the location of topographic divides and ground-water boundaries, and the consequent adjustments in ground-water recharge, will be addressed in specific reports for each study area. Geologic boundaries that affect the flow of ground water within study areas will also be addressed in the individual reports.

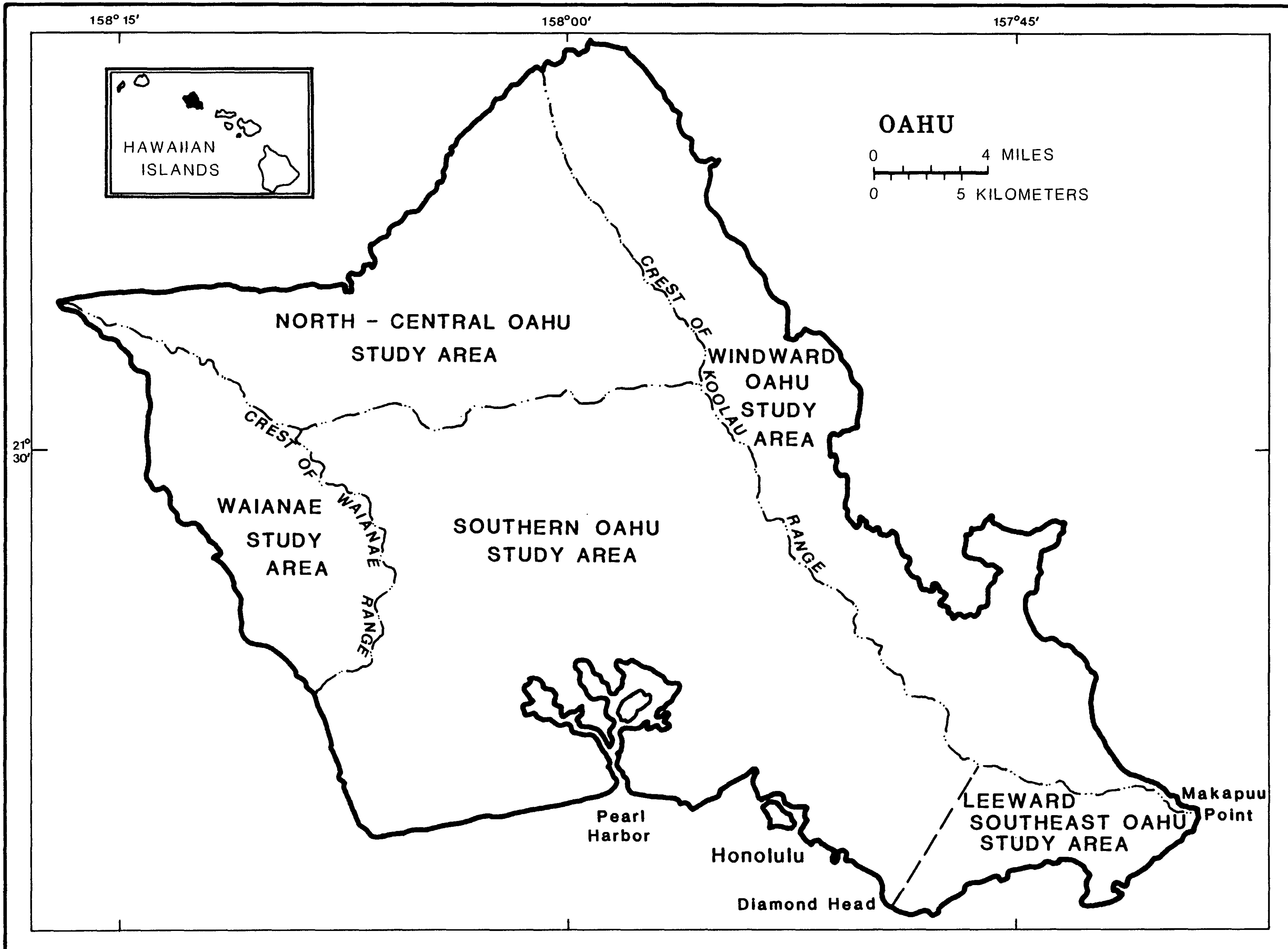


Figure 1. Hydrologic study areas on the island of Oahu.

Purpose and Scope

To define the hydraulics and hydrology of Oahu's ground-water system, the study areas need to be analyzed individually and their relationship to each other defined.

This report describes the aquifers in the leeward southeast Oahu study area. It presents a conceptual model of the aquifer flow system, and simulations of steady-state and transient flow conditions obtained from a finite-element aquifer model.

The report is the first of a series of reports defining Oahu's regional aquifer system.

Acknowledgment

The authors thank Clifford Voss of the U.S. Geological Survey, Northeastern Regional office, for introducing them to the AQUIFEM-SALT model (Voss, 1984a), developing the finite-element mesh, and guiding their efforts in applying the model.

LOCATION AND CULTURAL SETTING

Leeward southeast Oahu has an area of 23.4 square miles (fig. 2). The area is bounded on the north by the crest of the Koolau Range, on the south and east by the Pacific Ocean, and on the west by the Kaau rift zone, represented by a southwest-trending line from Kaau Crater at the crest to Diamond Head Crater at the coast.

It is unlikely that the Palolo valley fill, thought by Wentworth (1938) to be the western boundary of the study area, could be the cause of the 10-foot head difference that marks the separation of the ground water in the study area, from the ground water in the Kaimuki area to the west. At low elevations, the relatively impermeable valley fill is deep enough to affect the flow of ground water. However, at high elevations, the fill is not deep enough to intersect the water table and ground-water levels would be nearly the same in the two areas if not for the boundary created by the Kaau rift.

For this study, leeward southeast Oahu can be further divided into two areas; the Waialae area bounded on the west by the Kaau rift zone and on the east by a northeast-trending line of dikes, and the Wailupe-Hawaii Kai area which comprises the remainder of the study area.

Population

In 1980, the State population was 963,617 of whom 760,926 or almost 80 percent resided on the island of Oahu (State of Hawaii, 1980). This 80 percent of the population live on about nine percent of the total land area yielding an average density on Oahu of about 1,300 persons per square mile. The study area has a population of about 50,000 most of whom reside in the heavily developed valley floors and narrow coastal plain from Diamond Head to Koko Head.

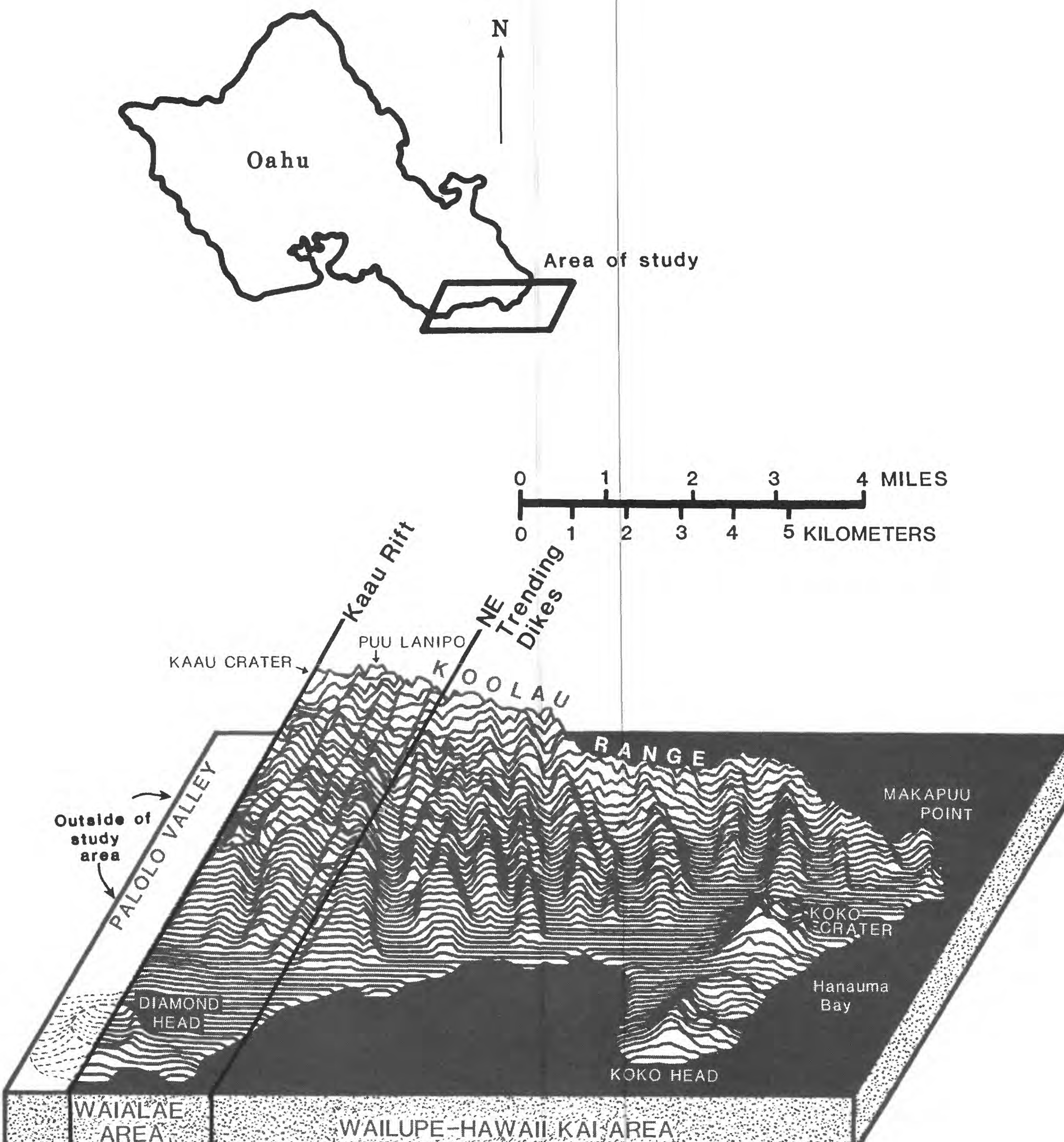


Figure 2. Leeward southeast Oahu study area.

Development

The island of Oahu is the hub of commerce, industry, and government in the State of Hawaii. Most of these activities are located west of the study area between Diamond Head and Pearl Harbor. The leeward southeast Oahu study area lies east of the center of activities and serves as a major residential and recreational area. From the eastern flank of Diamond Head to Makapuu Point virtually every valley floor and several intervalley ridges are developed for residential use.

Prior to statehood in 1959, the principal residential area was near Waialae-Kahala in the southern part of the Waialae area. Elsewhere, most of the population was involved in small-scale farming, raising pigs, vegetables, and flowers. Marsh areas and brackish-water springs, resulting from the near-shore discharge of groundwater, occurred across the area, but these have since been destroyed by urban development. Presently, scenic areas, surfing beaches, and two golf courses offer recreational opportunities to both residents and visitors.

PHYSICAL SETTING

Climate

Hawaii has a subtropical climate characterized by mild and equable temperature year round, persistent northeasterly tradewinds, moderate humidity, and extreme differences in rainfall within short distances. In most areas of the State including the study area, there are two seasons; summer between May and October, with warm, dry weather, and winter between November and April, with cooler temperatures, more cloudy rainy conditions, and a less dominant tradewind pattern.

Blumenstock and Price (1967) recognized seven climatic subregions in Hawaii based on major physiographic features and orientation to windward or leeward exposure. The southeast Oahu study area consists of two climatic subregions; the leeward lowlands, and the leeward mountain slopes.

The leeward lowlands have slightly higher daytime temperatures and slightly lower nighttime temperatures than in the windward lowland locations. Dry weather predominates, interrupted infrequently by light tradewind showers or major storms. The leeward mountain slopes have greater rainfall than the leeward lowlands, but generally significantly less rainfall than at the same elevation on the windward slopes. Temperature extremes and cloud cover are less on leeward slopes than on windward slopes. The mean annual temperature of the study area is about 75° F. The warmest and coolest months differ on the average by only 6.5° F.

Rainfall on the study area averages 50 inches annually or 56.8 Mgal/d (million gallons per day) (fig. 3). The isohyets indicate a decrease in rainfall west to east across the study area, from about 118 inches near Kaau Crater to about 30 inches at Makapuu Point. The rainfall gradient from north to south is quite steep, especially at the western end of the study area (Kaau Crater to Diamond Head). Most of the residential areas receive between 30 and 35 inches annually.

Topography

Most of the leeward southeast Oahu study area consists of the eroded southeastern flank of the Koolau Volcano. The Koolau crest is highest at Puu Lanipo, 2,621 ft above sea level, and decreases eastward to about 400 ft at Makapuu Point. The shape of valleys in southeast Oahu results from the combined effects of stream erosion, and deposition from recent volcanic eruptions and higher stands of the sea. Thus, the valleys are U-shaped to box-shaped in their lower reaches, where deposition was dominant and V-shaped with amphitheater heads in the upper reaches. The steep, corrugated inter-valley ridges extend almost to the shore.

The valleys tend to broaden below about the 200-ft altitude and join a narrow coastal plain. Near Diamond Head and Koko Head Craters, the coastal plain is significantly enlarged by the ash deposits resulting from the eruptions at these craters.

In addition to the Koolau crest and the deeply incised narrow valleys, the dominant landscape features are the craters and vents associated with the Quaternary Honolulu Group. Diamond Head, Kaau, and Kaimuki Craters are located at the western boundary of the study area, and Koko Head, Koko Crater, and Hanauma Bay Crater are at the eastern boundary (fig. 4).

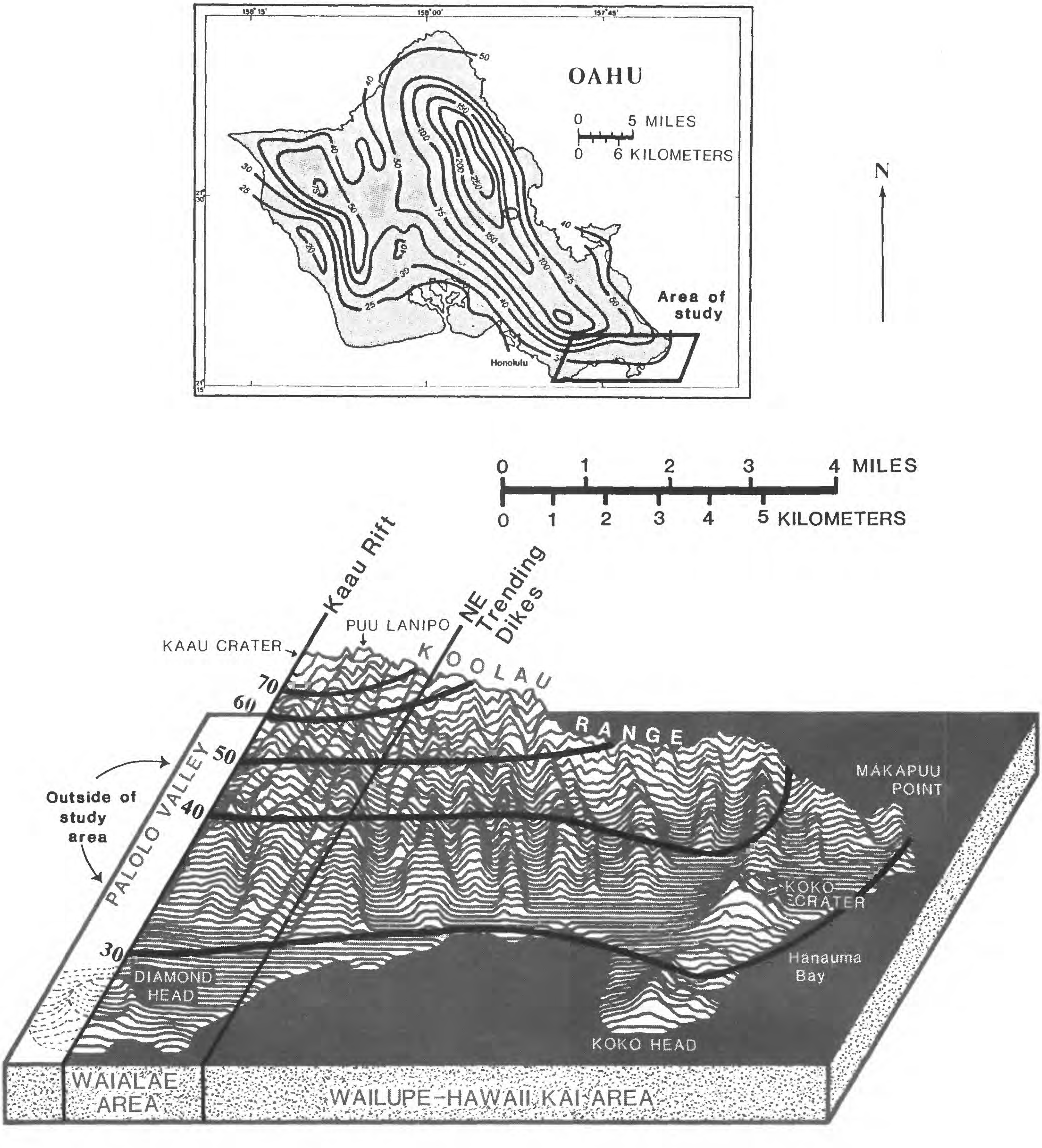


Figure 3. Oahu mean annual rainfall in inches (Schroeder and Meisner, 1980).

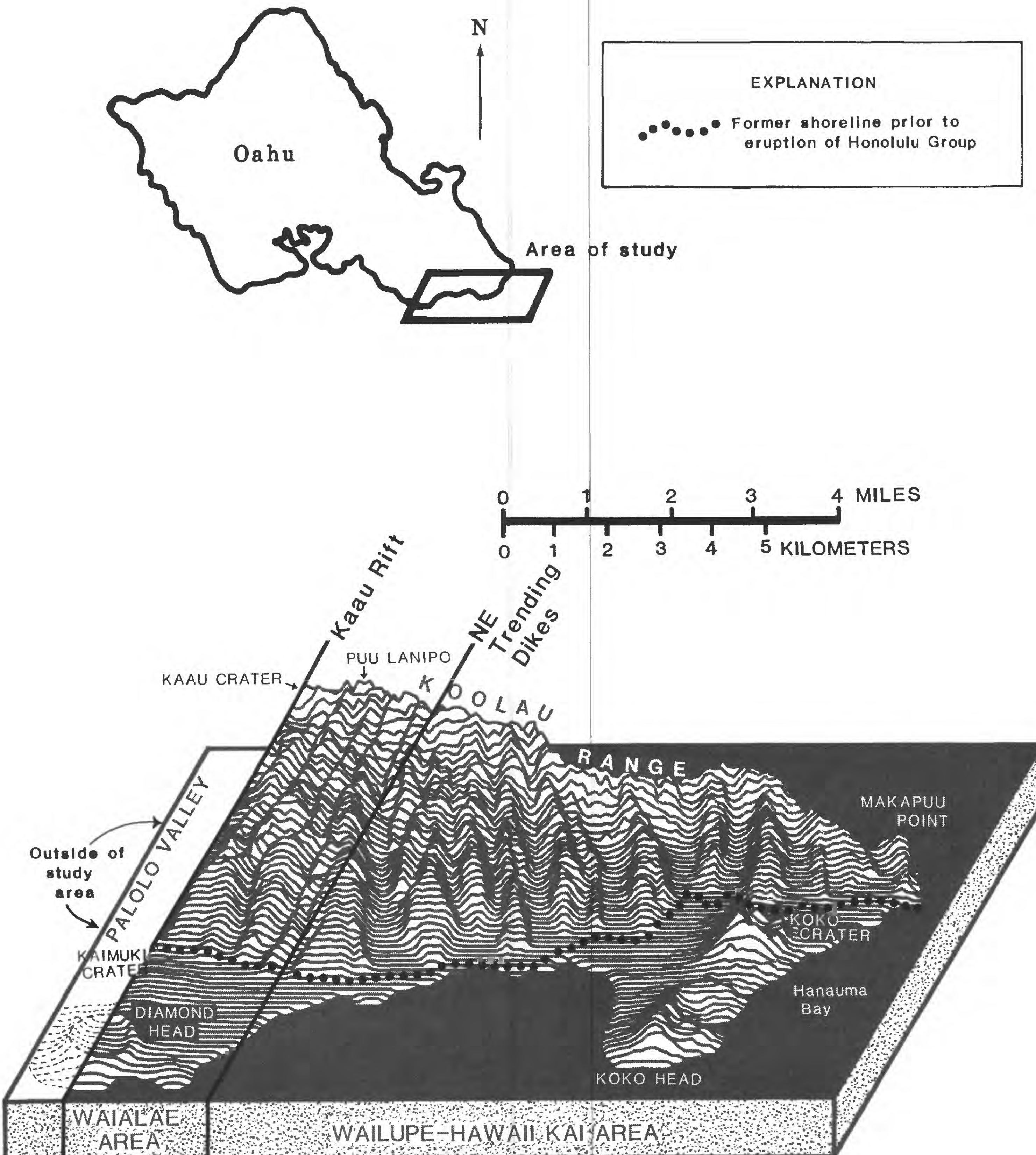


Figure 4. Dominant landscape features of leeward southeast Oahu.

Geology

The following discussion of the volcanic history and description of the rocks of southeast Oahu are based on the investigations of Stearns and Vaksvik (1935), Palmer (1921 and 1955), Wentworth (1938), Wentworth and Jones (1940), and Takasaki and Mink (1982).

Oahu was formed by the building and coalescing of the Koolau and Waianae shield volcanoes. Each volcano has a collapsed caldera at or near its summit with two principal rift zones and one minor rift zone extending outward from the caldera area (fig. 5). The shield volcanoes are built primarily of thin basaltic lava flows which form slopes of 3 to 10 degrees. The leeward southeast Oahu study area includes parts of the southeast and southwest rift zones. The Kaau rift and a line of northeast trending dikes about 1.5 miles to its east are features of the southwest rift zone. The southeast rift zone, along the Koolau crest, is one of the two main fissure zones from which Koolau lavas emanated. Extensive erosion occurred during a long period of quiescence following the initial mountain-building phase of volcanic activity. This erosion resulted in the deposition of sediments in coastal areas which helped to form a narrow coastal plain. The coastal plain was further developed as coral reefs grew and eroded during sea-level fluctuations that accompanied Pleistocene glaciation in North America and Europe. Thus, fossil coral reefs and marine and terrestrial sediments make up the bulk of the coastal-plain deposits which form a caprock of low permeability over the highly permeable Koolau lavas. The long period of volcanic quiescence was followed by a renewal of volcanic activity in southeastern Oahu which produced the volcanic rocks of the Honolulu Group.

In the study area, the Honolulu Group (fig. 6) is represented by Diamond Head, Kaimuki Crater, Mauumae Crater, Kaau Crater along the Kaau rift, which is a reactivated rift of the Koolau volcano, and by Koko Head and Koko Crater along the Koko rift, a rift of only the Honolulu Group. The rocks of the Koko rift consist almost entirely of ejecta, and some lava flows, of the post-erosional Honolulu Group. In general, lava flows of the Honolulu Group are thicker and more massive than the older Koolau lavas. A generalized geologic map (fig. 6) shows the distribution of the principal rock types.

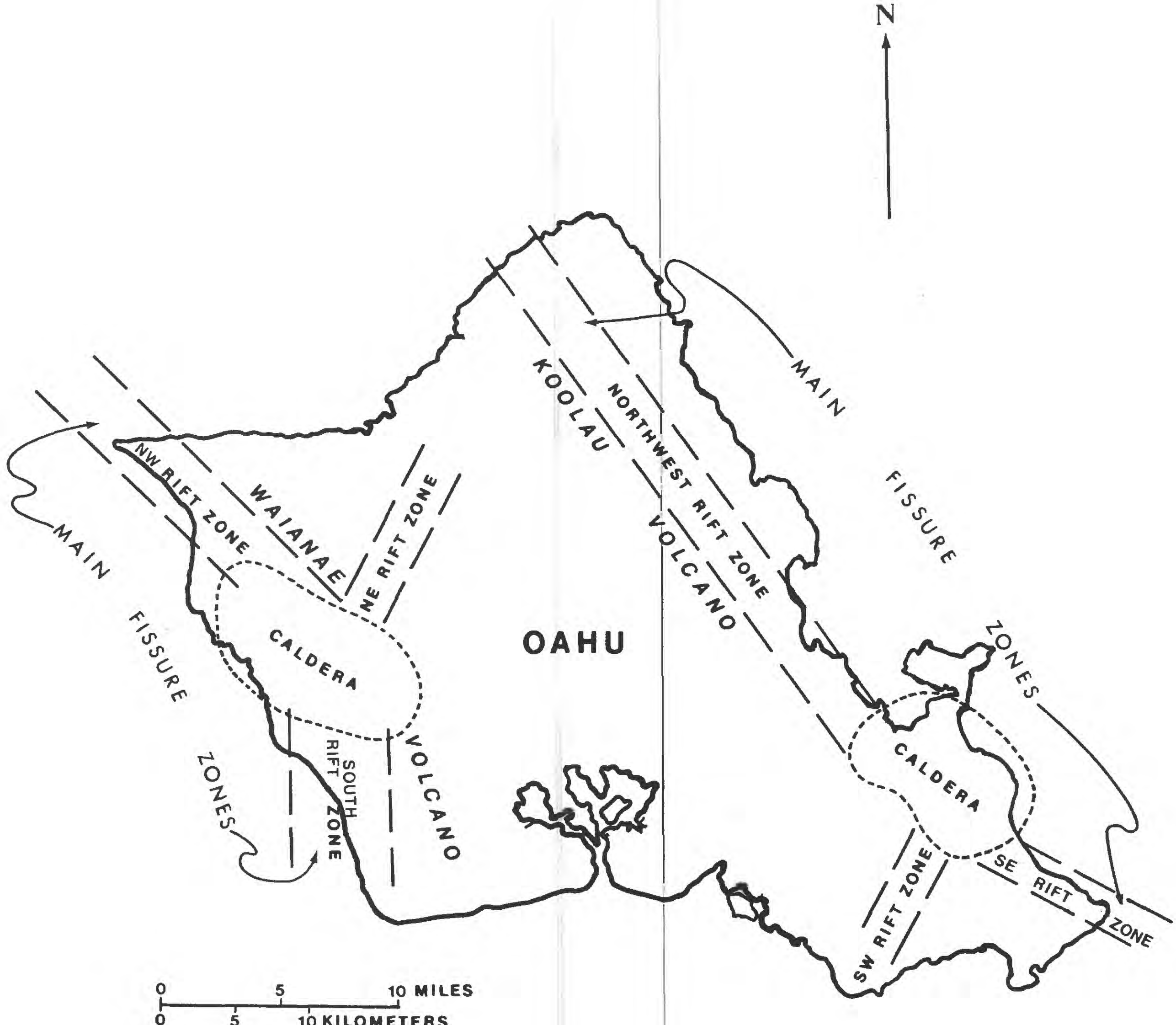


Figure 5. Rift zones and calderas of Koolau and Waianae volcanoes on the Island of Oahu (modified from Macdonald, 1972).

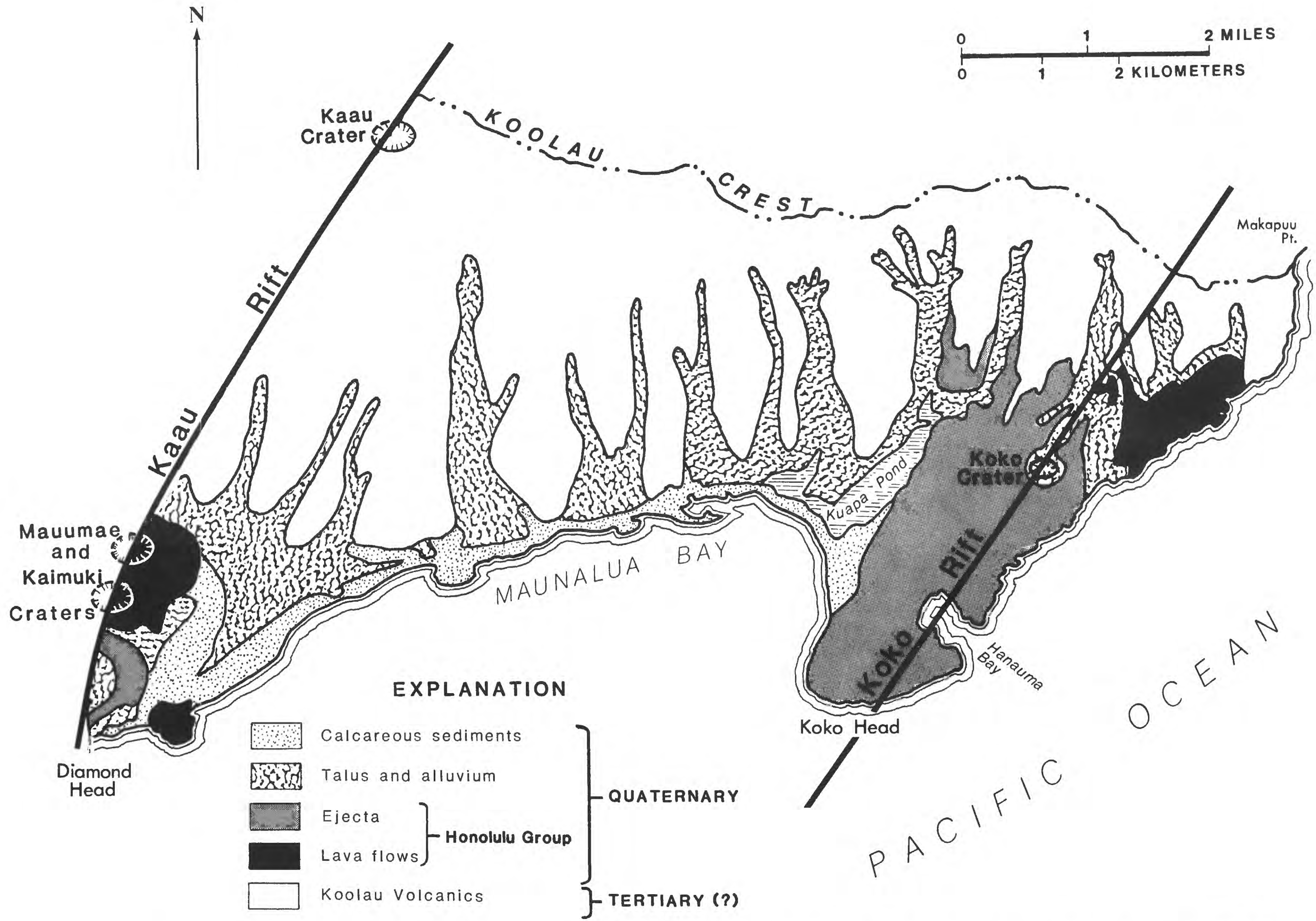


Figure 6. Generalized geologic map of leeward southeast Oahu (geology modified from Stearns, 1939).

The southeast rift zone separates ground water on the leeward side of the crest from that on the windward side. Where exposed by erosion, the rift zone is marked by numerous dikes, (fig. 7) which are vertical sheets of dense rock that, in their molten state, rose from deep within the island to feed the lava flows that erupted from the rift zone. The number of dikes is greatest in the central part of the zone, the "dike complex" (Stearns and Vaksvik, 1935), averaging more than 100 dikes per mile of horizontal distance (Macdonald, 1956), and usually composing more than 10 percent of the total rock volume. Dike occurrence decreases to between 10 and 100 dikes per mile in the "marginal dike zone" adjacent to the dike complex, and this number declines abruptly at the edges of the rift zone (Macdonald and Abbott, 1970). The dikes in the marginal dike zone make up less than 5 percent of the total rock volume. Generally, the strike and alignment of dikes is the same in each zone.

Dikes number much fewer than 100 dikes per mile in the Kaau rift and even less in the Koko rift and in the line of northeast trending dikes (Takasaki and Mink, 1982). The strike and alignment of dikes in the study area are nearly parallel to the lava flows and the direction of ground-water flow. This alignment does not impound water to high elevations as effectively as in other areas of Oahu where dikes are perpendicular to the direction of ground-water flow (Takasaki and Mink, 1982). However, dikes in the Kaau rift and the line of northeast trending dikes act as barriers to the lateral flow of ground water between the ground water of Kaimuki (to the west of the study area), Waialae, and Wailupe-Hawaii Kai.

Water-Bearing Rocks

The rocks of leeward southeast Oahu include dike-free and dike-intruded lava flows, breccia, tuff, cinders, and sedimentary material of volcanic origin. Coastal-plain deposits contain sedimentary rocks of volcanic origin, clays, coral, calcareous beach sand, and dunes. Permeability and the nature of ground-water occurrence for each of these rock types are presented in table 1.

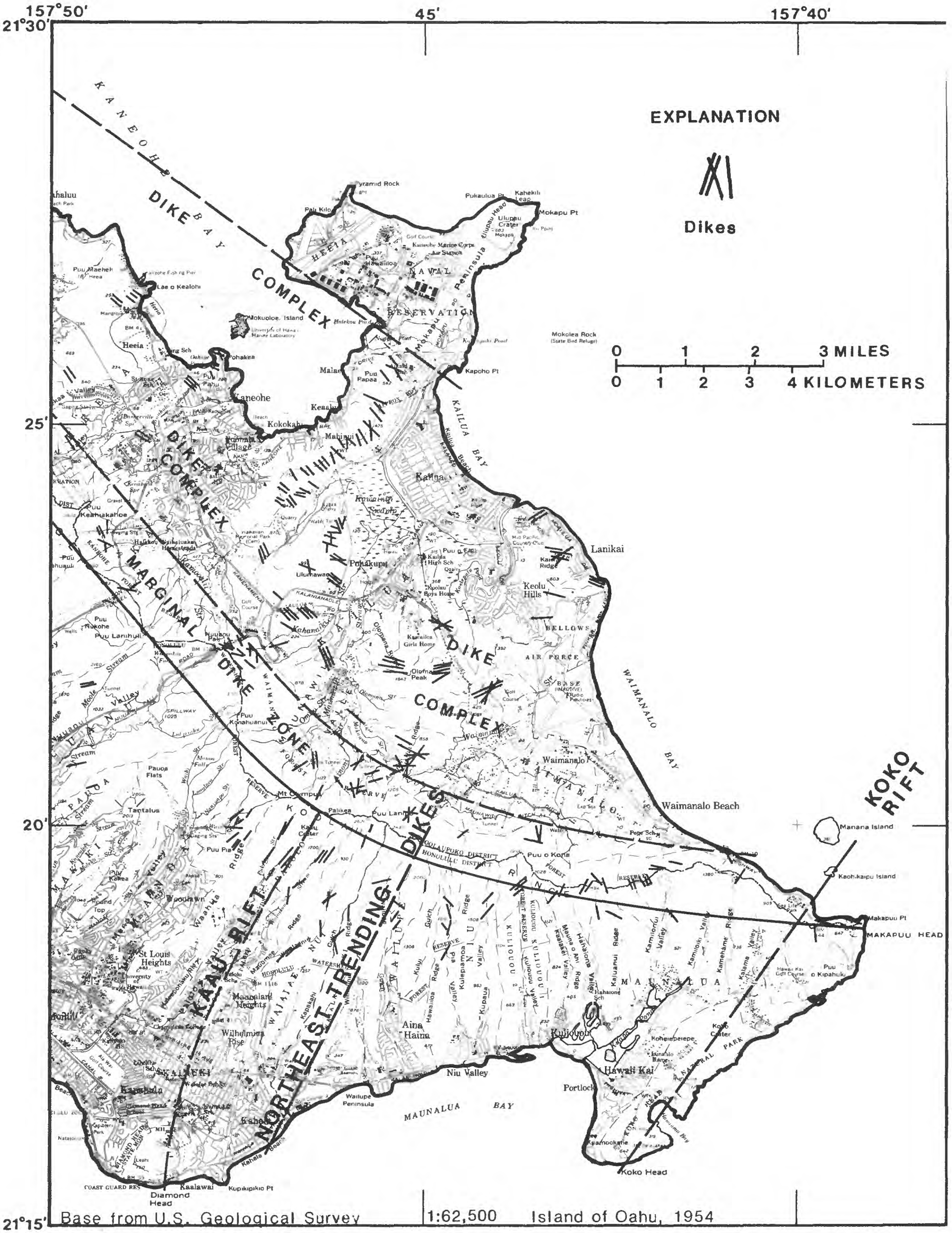


Figure 7. Dikes associated with the dike complex, marginal dike zone, Kaau rift, Koko rift and other minor rifts in southern Oahu (modified from Takasaki and Mink, 1981).

Table 1. Water-bearing properties of the rocks and occurrence of ground water in leeward southeast Oahu

(Modified from Takasaki and Mink, 1982)

Rock type	Permeability	Hydraulic conductivity (K) (ft/d)	Ground-water occurrence: Principal	Ground-water occurrence: Secondary
Sedimentary material				
Coral				
In situ	Moderate to high	100 to 1000	Basal*	Perched.
Reworked	Low to moderate	1 to 500	do.	Do.
Consolidated	Low	1 to 100	do.	Do.
Unconsolidated	Moderate to high	100 to 1000	do.	Do.
Dunes				
In situ	Low to moderate	1 to 500	Perched	Basal.
Reworked	do.	1 to 500	Basal	Perched.
Consolidated	Low	1 to 100	Perched	Basal.
Unconsolidated	Low to moderate	1 to 500	Basal	Perched.
Sand				
Consolidated	Low to moderate	1 to 500	Basal	
Unconsolidated	Moderate to high	100 to 1000	do.	
Lagoonal				
Sands				
In situ				
Consolidated	Low	1 to 100	Basal	
Unconsolidated	Low to moderate	1 to 500	do.	
Muds				
In situ				
Consolidated	Very low	less than 1	Perched	
Unconsolidated	Very low	do.	do.	
Alluvium				
Younger				
In situ	Low to moderate	1 to 500	Perched	Perched.
Unconsolidated	do.	1 to 500	do.	Do.
Older				
In situ	Very low	less than 1	Perched	
Reworked	do.	do.	do.	
Consolidated	do.	do.	do.	
Unconsolidated	Low	1 to 100	do.	Basal.
Volcanic				
Honolulu Group				
Inside caldera				
Lava flows	Low to moderate	1 to 500	Perched	
Cinders	Low	1 to 100	do.	
Tuff	Low	1 to 100	do.	
Outside caldera				
Lava flows				
Dike complex	Low to moderate	1 to 500	do.	
Marginal dike zone	do.	1 to 500	do.	
Dike-free	High to very high	500 to 1000	Basal	Perched.
Cinders	Low to moderate	1 to 500	Perched	
Tuff	Low	1 to 100	Basal	Perched.
Saprolite	Very low	less than 1	Perched	
Koolau Volcanics				
Inside caldera				
Lava flows	Low	1 to 100	Dike-impounded	Perched.
Breccia	do.	1 to 100	Perched	
Outside caldera				
Dike complex	Low to moderate	1 to 500	Dike-impounded	Perched.
Marginal dike zone	Moderate to high	100 to 1000	do.	Basal.
Dike-free	Very high	greater than 1000	Basal	
Breccia	Low	1 to 100	Perched	
Saprolite (highly weathered rock)	Very low	less than 1	do.	

* Basal refers to the lens of freshwater floating on seawater.

SURFACE WATER

Sixteen streams drain the study area and flow in the same southerly direction from the Koolau crest (fig. 8). These streams are intermittent except for short stretches near the head of some streams where perennial flow is low.

The streams are short, have steep gradients, and generally flow in narrow rectangular channels that are roughly normal to the crest of the Koolau Range. Of the 16 streams, 10 have no well-defined tributaries and 6 streams have one or more. In general, the drainage basins are shorter and wider in the eastern part of leeward southeast Oahu (Wailupe to Makapuu) than in the western part. No perennial streamflow reaches the ocean in the study area.

Surface-Water Data

With the exception of Waiomao Stream in the northwest corner of the study area, very little surface-water data exist. The U.S. Geological Survey operated a recording gage station (no. 2460) on Waiomao Stream from June 1926 through September 1971 (fig. 8). The drainage area above the gage is 1.04 square miles and the stream has a mean daily discharge of 1.86 ft^3/s (cubic feet per second) based on 45 years of record. The maximum discharge during this period occurred on April 11, 1930 when a peak of 1,550 ft^3/s was recorded. There were frequent periods of no flow during dry weather.

Crest-stage partial-record stations in Wailupe Gulch (no. 2475) and Kuliouou Valley (no. 2479) are designed to record peak stages throughout the year from which the annual peak discharge is determined. Since 1958, annual peak flows have been recorded for Wailupe Gulch. The highest measured flow was 3,600 ft^3/s which occurred on Dec. 18, 1967. In Kuliouou Valley, records of annual peak flows are available for 1958-59, and from 1970 to present. The highest flow during the period was 1,290 ft^3/s on Jan. 6, 1982.

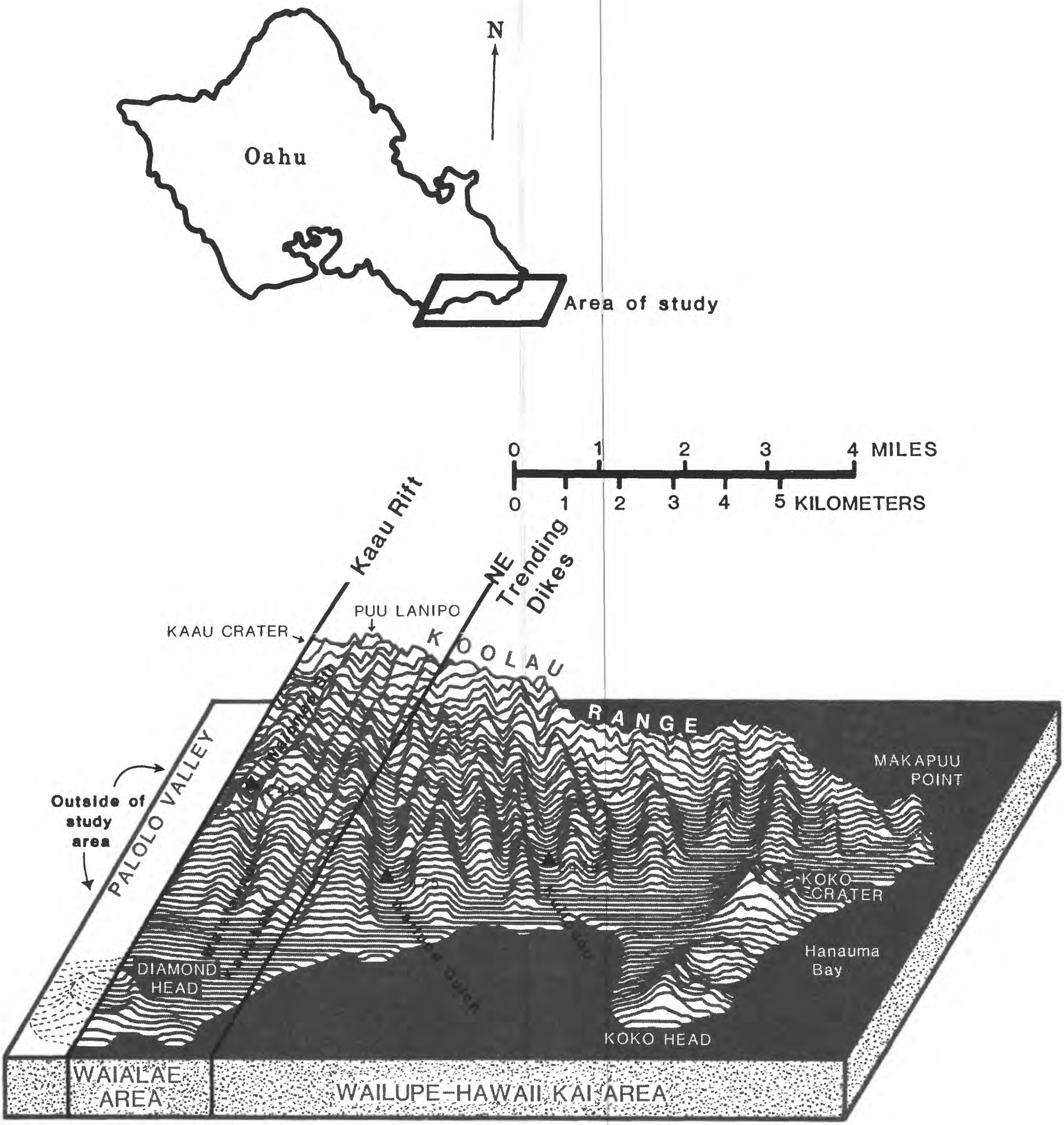


Figure 8. Streams in leeward southeast Oahu.

Flow to the sea occurs only during and after heavy rainfall. Streams in the Waialae area are perennial only at their headwaters near the Koolau crest. Data are insufficient to quantify the perennial flow, but a qualitative assessment can be made. Generally, the magnitude of perennial flow in a stream cut into dike-intruded rocks depends on the orientation of the dikes to the ground-water flow direction, size of the dike-impounded ground-water reservoir, quantity and frequency of recharge to the reservoir, and how deeply the stream has eroded into the reservoir. This general statement can also be made about perched water in a drainage basin.

In the Waialae area, the major perennial flow is from the headwaters of Waiomao Stream. Wentworth (1938) noted persistent seepage and what he termed "nearly perennial pools" in Waialaenui and Kapakahi Valleys. However, Takasaki and Mink (1982) did not find this to be true during their investigation. The only perennial flow they observed was in Wailupe Gulch where a small flow of 0.1 to 0.2 Mgal/d originated in a small amphitheater-like valley above an altitude of 1,120 feet. In summary, the amount of perennial flow in this part of the study area is quite small when compared to the mean annual rainfall. Streams in the eastern part (Hawaii Kai) of the study area have no perennial flow even in their headwaters and quickly go dry after rain storms.

The estimated mean annual surface runoff for each basin in the study area was determined from a multiple regression equation developed by Matsuoka (written commun., 1981), which uses mean annual basin runoff as the dependent variable, and mean annual basin rainfall, drainage area, stream slope, and percent forest cover as the independent variables. The mean annual runoff from the study area is 6.4 Mgal/d. The estimated mean annual runoff for the individual basins ranges from 0.9 Mgal/d for the Waiomao basin to .05 Mgal/d for the Hawaii Kai golf course basin, northeast of Koko crater.

Surface-Water Development

Surface-water resources in the study area have not been developed. Because of the flashy nature of the streams and a lack of suitable sites capable of storing significant quantities of runoff, the development and utilization of streamflow is not feasible.

OCCURRENCE OF GROUND WATER

Dike-impounded water, perched water, and basal water are the three principal modes of ground-water occurrence on Oahu (fig. 9). Each of these will be discussed in relationship to the study area.

Dike-Impounded Water

Dike-impounded water refers to ground water impounded by volcanic dikes usually at high altitude in the interior of the island. Because of the vertical structure of the dikes this ground water does not come in contact with seawater. In the study area, reservoirs of dike-impounded water are located in the Kaau and southeast rift zones near the crest of the Koolau Range. Elsewhere in the study area, dikes are less common and trend nearly parallel to the direction of ground-water flow. Therefore, ground water is not impounded in these areas.

Around 1910, two tunnels were driven into the east wall of Kaea Valley on the southwest side of Kaau Crater. One tunnel, located at an altitude of about 1,130 feet was 100 feet in length. The tunnel was driven through dense Koolau lava which was broken by numerous joints. The maximum reported yield was about 100,000 gallons per day. The tunnel was in service until 1920 when the portal was clogged with debris and the yield had dropped to a trickle. The second tunnel, driven at an altitude of about 870 feet was 120 feet long and in dense Koolau Volcanics. No water was developed from this tunnel, and both tunnels were abandoned (Stearns and Vaksvik, 1935).

Palolo tunnel, located at the site of the former Waiomao Springs at an altitude of 990 feet on the west bank of Waiomao Stream, was dug in 1920. The tunnel is 180 feet long and penetrates the permeable clinker zone of an aa lava flow and one 4-foot-thick dike. This dike, like many others in the area, trends slightly east of north. Discharge from the tunnel is variable and appears to fluctuate with rainfall. Initial tunnel discharge was about 1.5 Mgal/d and lasted only a few months (Stearns and Vaksvik, 1935). The mean discharge in 1982 was 290,000 gallons per day (Honolulu Board of Water Supply, 1982). Water from the tunnel is used for domestic supply.

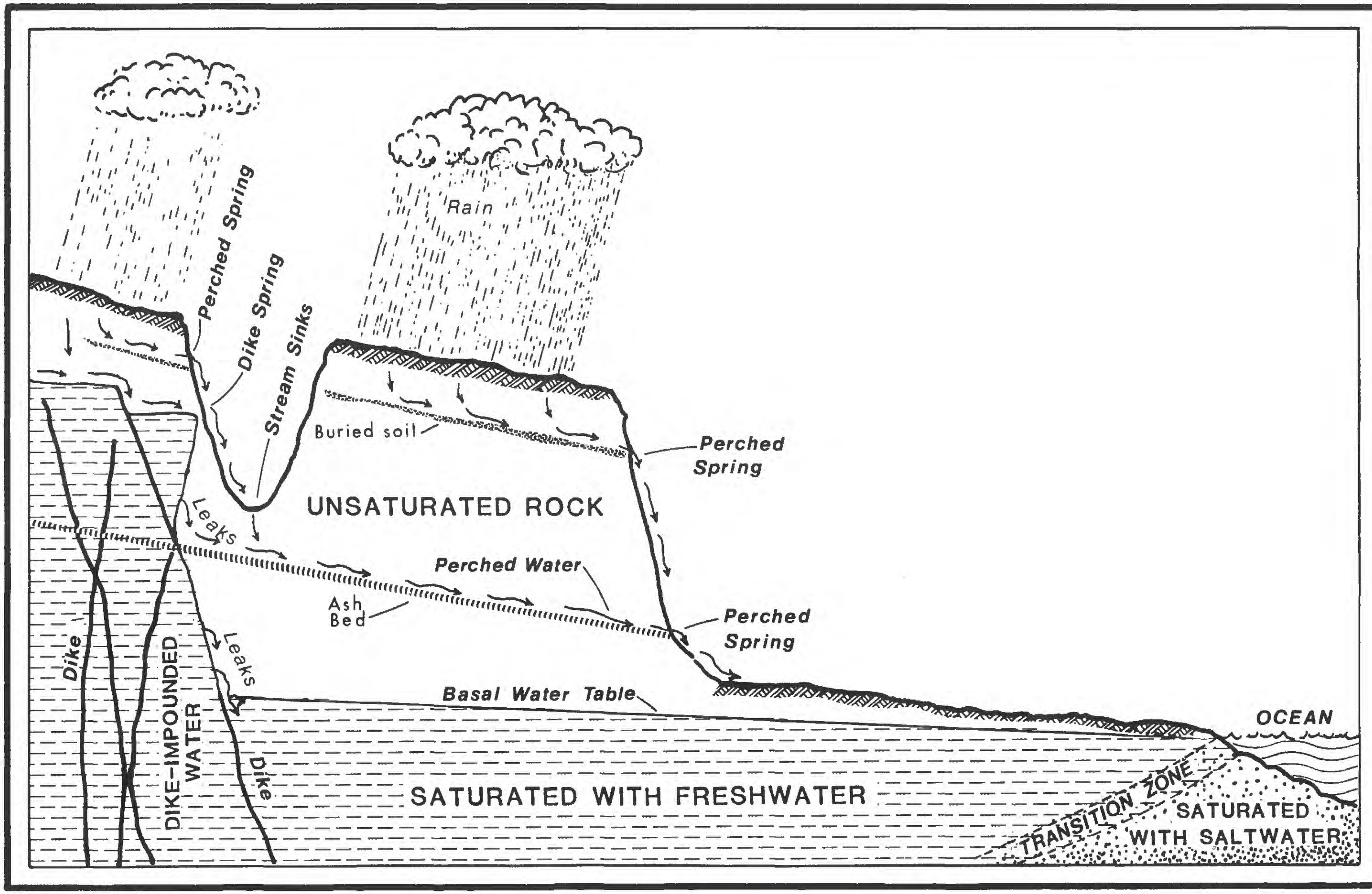


Figure 9. Diagram showing perched water, water confined between dikes, basal water, and perched and basal springs (modified from Stearns and Macdonald, 1946).

The small perennial flow observed near the heads of some valleys may be fed by the leakage of ground water through dikes, but no evidence of dike-impounded water in the middle and lower reaches of streams was found during field inspection by Takasaki and Mink, (1982).

Perched Water

Perched water refers to water held up by a formation of low permeability, which in Hawaii is usually a layer of weathered volcanic ash or alluvium. On Oahu the occurrence and importance of perched water is small compared to dike-impounded and basal water reservoirs and is important only locally. No evidence of significant discharges of perched water exists in the study area (Takasaki and Mink, 1982), although some of the flow in upper Waiomao Stream may result from ground water perched on sills or low angle dikes.

Basal Water

Basal water is a lens of fresh ground water that is stored near and below sea level and is in dynamic equilibrium with the underlying saline ground water. Basal water can be confined or unconfined. Basal water occurs in all rocks that extend below sea level except in the rift zones. Fresh to brackish water occurs in coralline limestone and dune sands of the narrow coastal plain. The Ghyben-Herzberg relation states that a freshwater lens, with density 1.000 g/cm^3 (gram per cubic centimeter), floating on saltwater, with density 1.025 g/cm^3, will have a thickness equal to 41 times the head of freshwater above sea level.

The basal water lens of the study area is divided into two distinct reservoirs (Takasaki and Mink, 1982) (fig. 10). Figures 11 and 12 are cross-sections showing the relative thickness of the lenses and the geologic features that separate them. Water levels shown on the two cross-sections were constructed primarily from data obtained from test-hole drilling by the Honolulu Board of Water Supply in 1936. The sections were located across the volcanic spurs of the Koolau Range at altitudes of 400 and 1,000 feet (Takasaki and Mink, 1982). The Kaau rift is an effective barrier between the Palolo reservoir and the Waialae reservoir. Between the Waialae area and the Wailupe-Hawaii Kai area the northeast trending dikes appear to be an effective barrier.

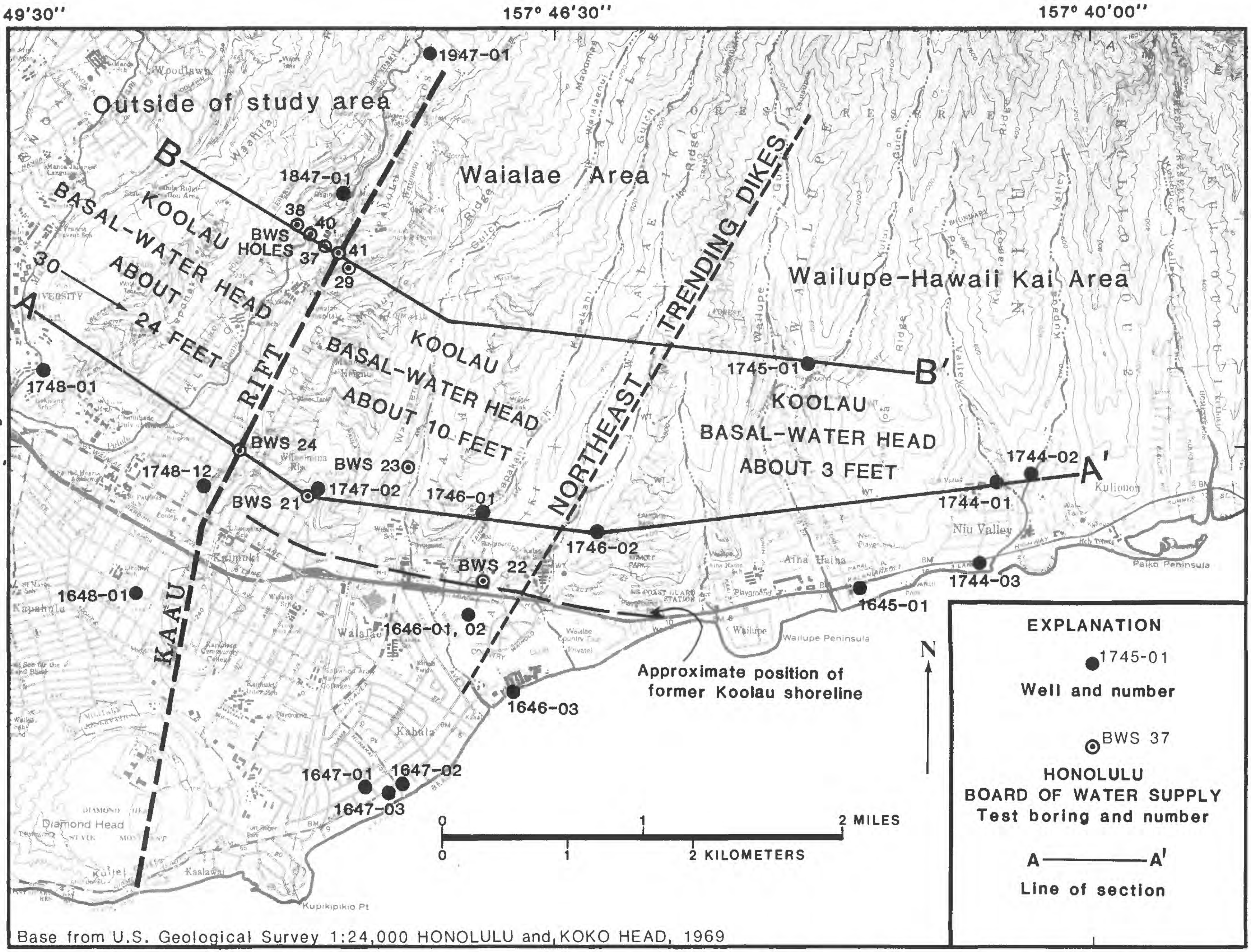


Figure 10. Part of leeward southeast Oahu showing location of selected wells and distinctive basal-water reservoirs of different heads (modified from Takasaki and Mink, 1982).

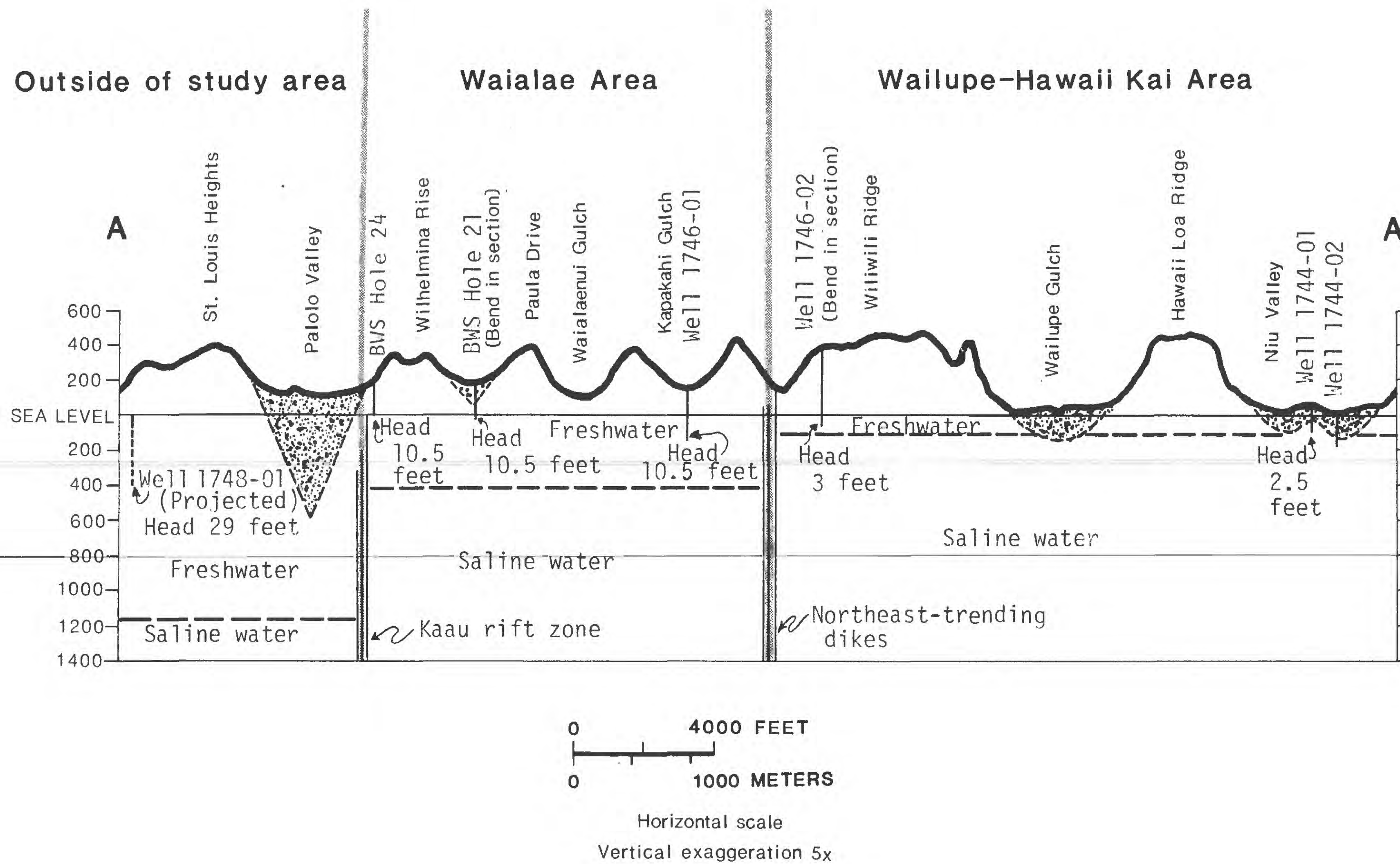


Figure 11. Section (A-A') across volcanic spurs at the 400-foot contour showing thickness of basal-water reservoirs (from Takasaki and Mink, 1982).

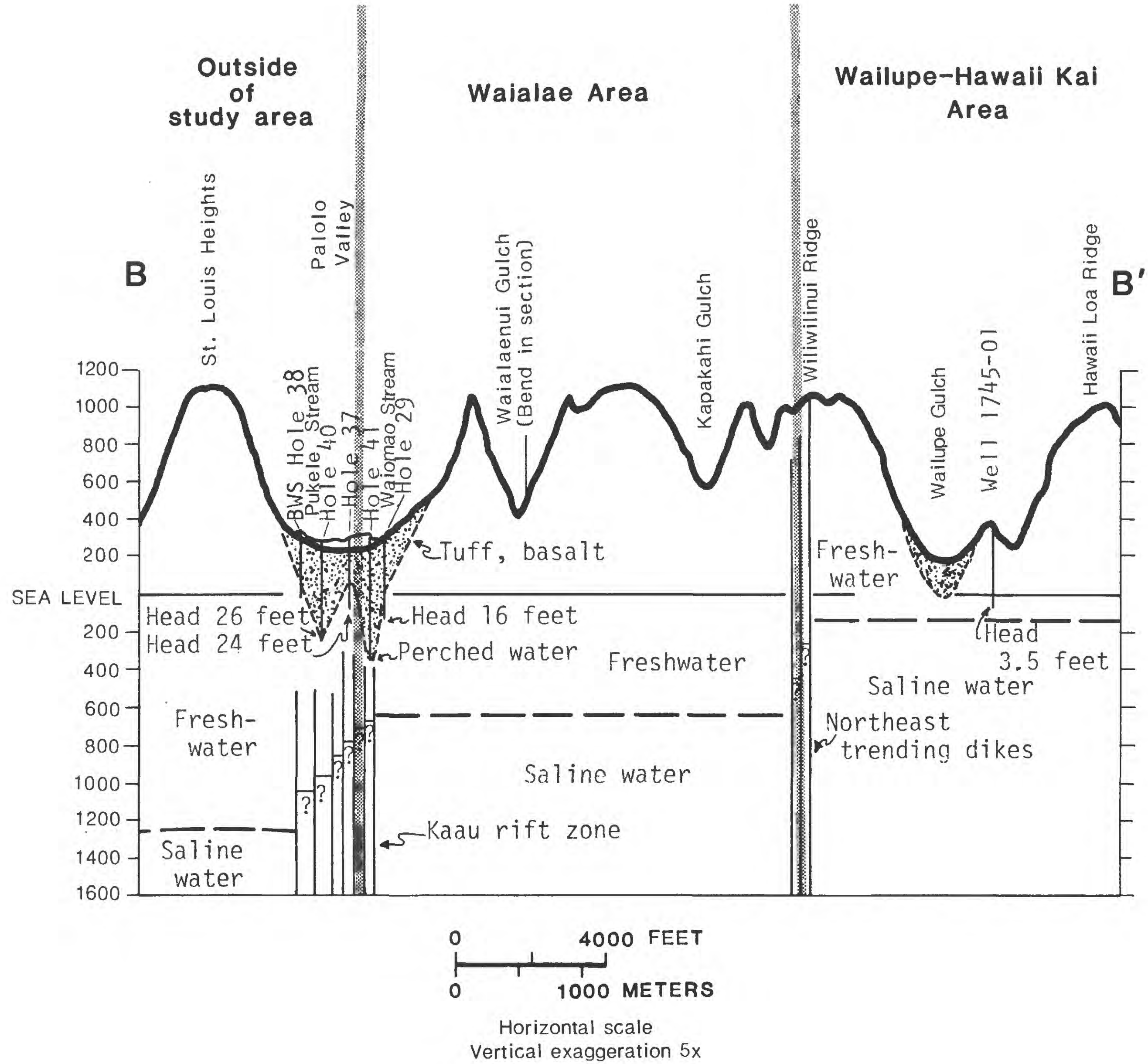


Figure 12. Section (B-B') across volcanic spurs at the 1,000-foot contour showing thickness of basal-water reservoirs (from Takasaki and Mink, 1982).

CALCULATION OF GROUND-WATER FLOW RATE THROUGH THE WAIALAE AND WAILUPE-HAWAII KAI AREAS

Knowledge of the quantity of water that flows through the aquifers of leeward southeast Oahu is vital to the descriptions and predictions of the behavior of these water resources. Because of the errors and assumptions inherent in any calculation of ground-water flow, two independent approaches were used in its determination. In the first approach, Darcy's law is used to determine ground-water flow rates using water-level data, knowledge of the aquifer's physical boundaries, and an estimate of hydraulic conductivity. In the second approach, a water budget, estimates of runoff and evapotranspiration are subtracted from rainfall, yielding rates of ground-water recharge, the source of flow calculated by Darcy's law.

Calculation of Ground-Water Flow Rate by Darcy's Law

Darcy's law states that:

$$Q = KAdh/dl \qquad (1)$$

where:

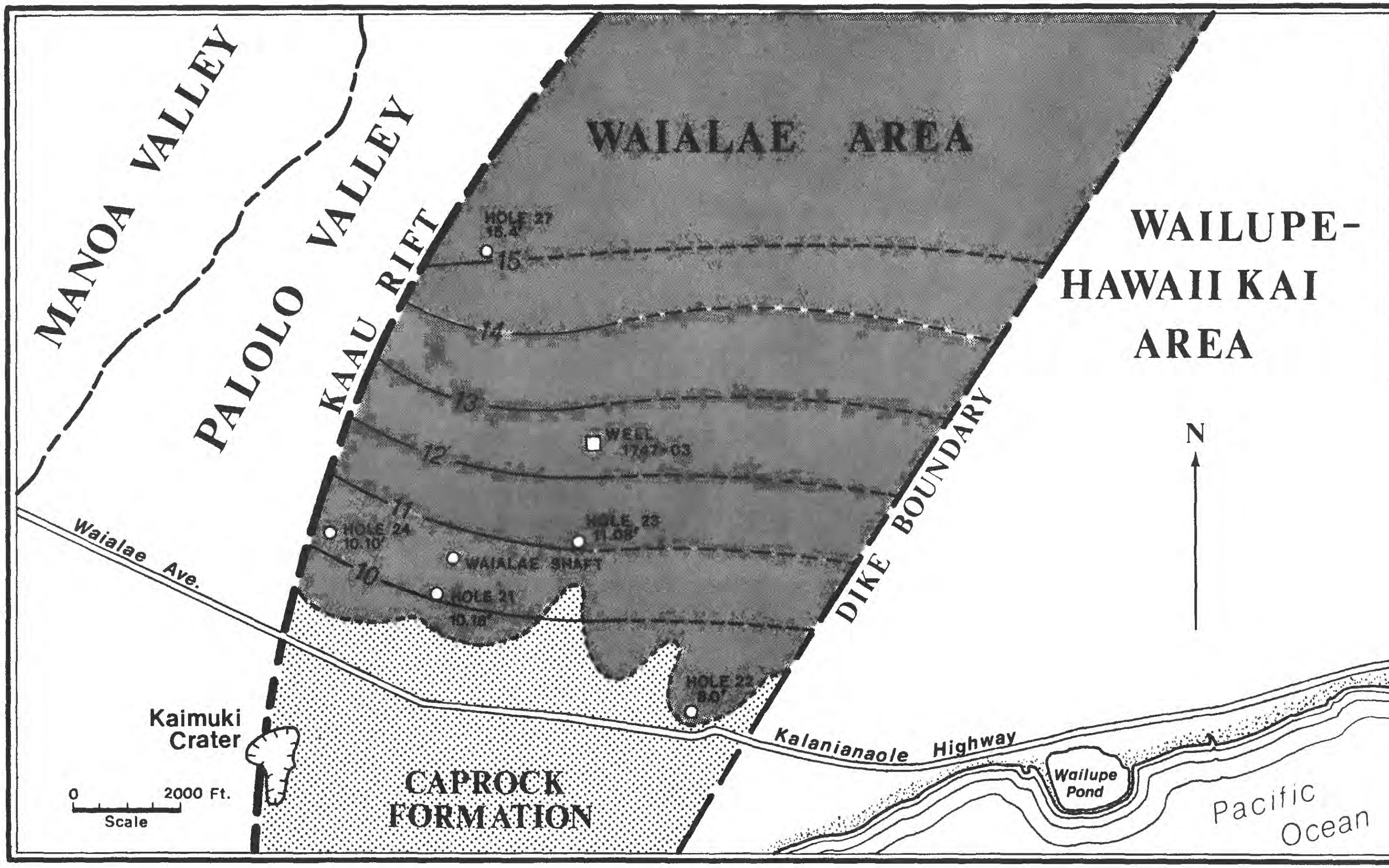
Q = ground-water flow through the study area (L^3/t)

K = hydraulic conductivity (L/t)

A = the cross sectional area through which flow occurs (L^2)

dh/dl = the slope of the water table or piezometric surface

In 1935 and 1936, the Honolulu Board of Water Supply (BWS) collected water-level data from several test wells in the Waialae area. A water-level- contour map constructed from these data (fig. 13) showed a hydraulic gradient of about 4 ft/mi (feet per mile) and, at the 10 foot water-level contour, a distance of 9,400 feet between the Kaau rift boundary and the northeast-trending dike boundary on the east.



EXPLANATION

——15--- Water level contour, dashed where uncertain. Contour interval is 1 foot.

o Hole 27 — Number and location of test hole with water level in 1936.

□ Well drilled since 1936

▬ - - ▬ Drainage divide

Figure 13. Water-level contour map of the Waialae area (modified from Wentworth, 1938).

Drill hole 27, (fig. 13), whose head of 15.4 feet provided the data for the hydraulic gradient of 4 ft/mi, is probably in the margin of the Kaau rift zone and not representative of the Waialae area. Well 1747-03 drilled in Waialae Nui in 1983, had a head of 11.6 feet indicating that the head gradient in the Waialae area is probably closer to 2.5 ft/mi than 4 ft/mi. The simulation of ground-water flow presented later gives a representative head near drill hole 27 of about 13 feet.

In June 1936, a pumping test at Waialae shaft produced data needed to calculate the hydraulic conductivity (K) of the aquifer in the Waialae area (Wentworth, 1938). Wentworth corrected his data without explanation, assumed a flow thickness of 200 feet, and calculated K to be 2,000 ft/d (feet per day). Takasaki and Mink (1982), used Wentworth's corrected data with the Theis nonsteady radial flow formula and also calculated a K value of about 2,000 ft/d, assuming a 200-foot thickness of flow. This value is unreasonably large considering that the rate of flow implied by K, coupled with a gradient of 2.5 ft/mi, is greater than the rate of rainfall over the recharge area. Hydraulic gradients in other Koolau basalt aquifers where no dikes are observed and where rainfall is relatively high are 1 ft/mi. The steep hydraulic gradient, relatively low rainfall, and presence of dikes imply that the hydraulic conductivity of this area is lower than the usual values of 1,000 to 2,000 ft/d calculated for dike-free Koolau lavas.

In addition, Wentworth observed significant upconing of saltwater at Waialae shaft prior to sealing of the pump sump floor. From this observation, an equation describing flow to a dug well through a hemispherical surface area (Bear, 1979, p. 345) seems preferable, to the Thiem equation employed by Wentworth (1938) describing radial flow to a vertical well. Eyre (1983) found that both equations produced similar results when applied to a partially-penetrating well that tapped the flank flows of the Koolau mountain. When drawdown, s, is substituted for Bear's head term, the following equation results:

$$K = \frac{1}{2\pi} \left(\frac{Q}{s_2 - s_1}\right) \left(\frac{1}{r_2} - \frac{1}{r_1}\right) \qquad (2)$$

where:

Q = flow rate from the pumped well (L^3/t)

K = hydraulic conductivity of the aquifer (L/t)

s = the observed drawdown at radius = r, from the pumped well (L).

r = radial distance from pumped well (L).

The flow rate during the Waialae Shaft test was 4,000 gallons per minute. The locations of the shaft and observation wells are shown in figure 13 and the data obtained from observation wells and the calculated K values obtained by use of equation 2 are presented in table 2.

Table 2. Waialae shaft (1747-02) pumping test data for calculation of aquifer hydraulic conductivity, June 10-20, 1936

[Constant pumping rate of 4,000 gal/min for 10 days; data from Wentworth, 1938, p. 193]

Observation well pair		Distance from pump (ft)		Drawdown (ft)		Hydraulic conductivity (K) (ft/d) (equation 2)
W1	W2	r1	r2	s1	s2	
21	23	690	2320	0.93	0.80	960
21	24	690	2610	.93	.79	930
21	22	690	4650	.93	.49	340
21	27	690	5750	.93	.54	400
23	24	2320	2610	.80	.79	590
23	22	2320	4650	.80	.49	85
23	27	2320	5750	.80	.54	121
24	22	2610	4650	.79	.49	68
24	27	2610	5750	.79	.54	102
						average K = 400 ft/d

If the aquifer was homogeneous, isotropic, and infinite in areal extent, all of the calculated K values presented in table 2 would be the same. The variability of K is an indication of heterogeneity of the aquifer as well as the effects of the Kaau rift and dike intrusions. In some parts of the Waialae area, water moves easily through the rocks and in other parts the rocks offer more resistance to flow. The observed hydraulic gradient of 2.5 ft/mi indicates that the effective K throughout the aquifer is relatively small compared to typical K values for dike-free Koolau lavas; therefore, K is assumed to be the average of the values presented in table 2, which is 400 ft/d.

The amount of water flowing through the Waialae area can be estimated from the information just presented. Again,

$Q = KAdh/dl$

Q = ground-water flow rate

K = 400 ft/d

$A = (41)(10)(9{,}400)$ by the Ghyben-Herzberg relationship and the measured width of flow at the ten-foot water-level contour

$dh/dl = 2.5/5{,}280$

and the ground-water flow through the Waialae area is:

$$Q = (400)(410)(9{,}400)(2.5/5{,}280) = 7.3 \times 10^5 \text{ ft}^3/\text{d} = 5.5 \text{ Mgal/d}$$

In the Wailupe-Hawaii Kai area the only water level data available are from 3 widely-spaced wells (elements 119, 152, and 216, fig. 14). These wells indicate a gradient of about 1.5 ft/mi and a width of flow of 22,000 ft at the 3.5-foot water-level contour. Assuming a hydraulic conductivity of 1,000 to 1,500 ft/d, as observed in many wells that tap dike-free Koolau lavas, the ground-water flux through the Wailupe-Hawaii Kai area is:

$$Q = (1{,}000)(41)(3.5)(22{,}000)(1.5/5{,}280) = 897{,}000 \text{ ft}^3/\text{d or } 6.7 \text{ Mgal/d.}$$

If K = 1,500 ft/d the resulting flow rate is 10.1 Mgal/d.

Water Budget

The purpose of this water budget is to determine the rate and spatial distribution of ground-water recharge. This information will aid in the prediction of long-term head changes resulting from additional pumpage that is planned for the leeward southeast Oahu area.

Estimates of the recharge rate through the western part of the study area have been reported by Stearns and Vaksvik (1935, p. 327) and Wentworth (1938, p. 257). Stearns and Vaksvik concluded that where annual rainfall was greater than 30 inches, approximately one third of the rainfall recharged the aquifer, and where annual rainfall was less than 30 inches, no recharge occurred. Wentworth thought that one fifth of rainfall in excess of 30 inches was a more correct factor for the determination of recharge.

Rainfall over southeast Oahu averages 57 million gallons per day (Mgal/d), or 50 inches per year over the 23 square mile area, as calculated from the isohyetal map produced by Schroeder and Meisner (1980) (fig. 3). Applying the factors of Stearn's and Vaksvik (1935) and Wentworth (1938), of one third and one fifth, recharge is 19 Mgal/d or 11 Mgal/d, respectively. A State Water Commission report (1979) estimated the sustainable yield of leeward southeast Oahu to be 5 Mgal/d, or about one fourth to one half of recharge. Sustainable yield is defined as the amount of water that can normally be withdrawn from an aquifer without producing undesirable effects.

The estimates of recharge obtained by Stearns and Vaksvik and Wentworth used mean annual data over large areas. Mather (1978) has shown that recharge is more accurately calculated by using observed daily data rather than monthly or annual averages. Using long-term mean data generally overestimates evapotranspiration and underestimates recharge because actual evapotranspiration is often much less than the potential evapotranspiration used in the budget. A computer watershed model using actual storm data and basin characteristics has accurately simulated the hydrologic process in Moanalua Valley, Oahu, Hawaii (Shade, 1984). The model shows that ground-water recharge in this wet valley, where mean annual rainfall is 100 in./yr (inches per year), is 43 percent of rainfall. The difficulty in obtaining the required short-term data over a broad area precluded such an approach for this study.

Giambelluca (1983) produced a water budget computed from observed monthly data from 1946 to 1975 for 258 water-balance zones that compose the Honolulu and Pearl Harbor basins, northwest of this study area. His results for the Pearl Harbor basin indicate that approximately 44 percent of rainfall becomes recharge to the aquifer, a smaller fraction recharging dry areas and a larger fraction recharging wet areas. An approach similar to Giambelluca's, which addressed the spatial and temporal variations in recharge, was used in this study.

Recharge to the aquifers of leeward southeast Oahu was calculated using a water-budgeting approach introduced by Thornthwaite and Mather (1955). Their equation states that:

Rainfall - runoff - recharge - evapotranspiration - change in soil storage = 0. (3)

The equation was solved using mean monthly data for each of the 284 elements of the southeast Oahu finite element mesh (fig. 14) created for the ground-water flow model presented in this report. Mean monthly data were used to incorporate seasonal fluctuations into the calculations. Annual data were considered to be too coarse and daily data over the area do not exist.

Calculation of Water Budget Parameters

Rainfall

Mean monthly rainfall for each element was determined by first transferring mean annual rainfall from the isohyetal map (fig. 3) to the elements of the grid and then applying regression equations that calculate monthly values. The 12 monthly regression equations, from Stidd and Leopold (1950), are based on the linear relationship between mean monthly and mean annual rainfall determined from many long-term rain gage records on Oahu.

Rainfall decreases from 120 in./yr in the mountainous northwest part to 30 in./yr in the south and east parts of the study area. The mean annual rainfall over the study area is 57 Mgal/d, of which 24 Mgal/d (62 in./yr) is over the 8.1-mi^2 Waialae area, and 33 Mgal/d (45 in./yr) is over the 15.3-mi^2 Wailupe-Hawaii Kai area.

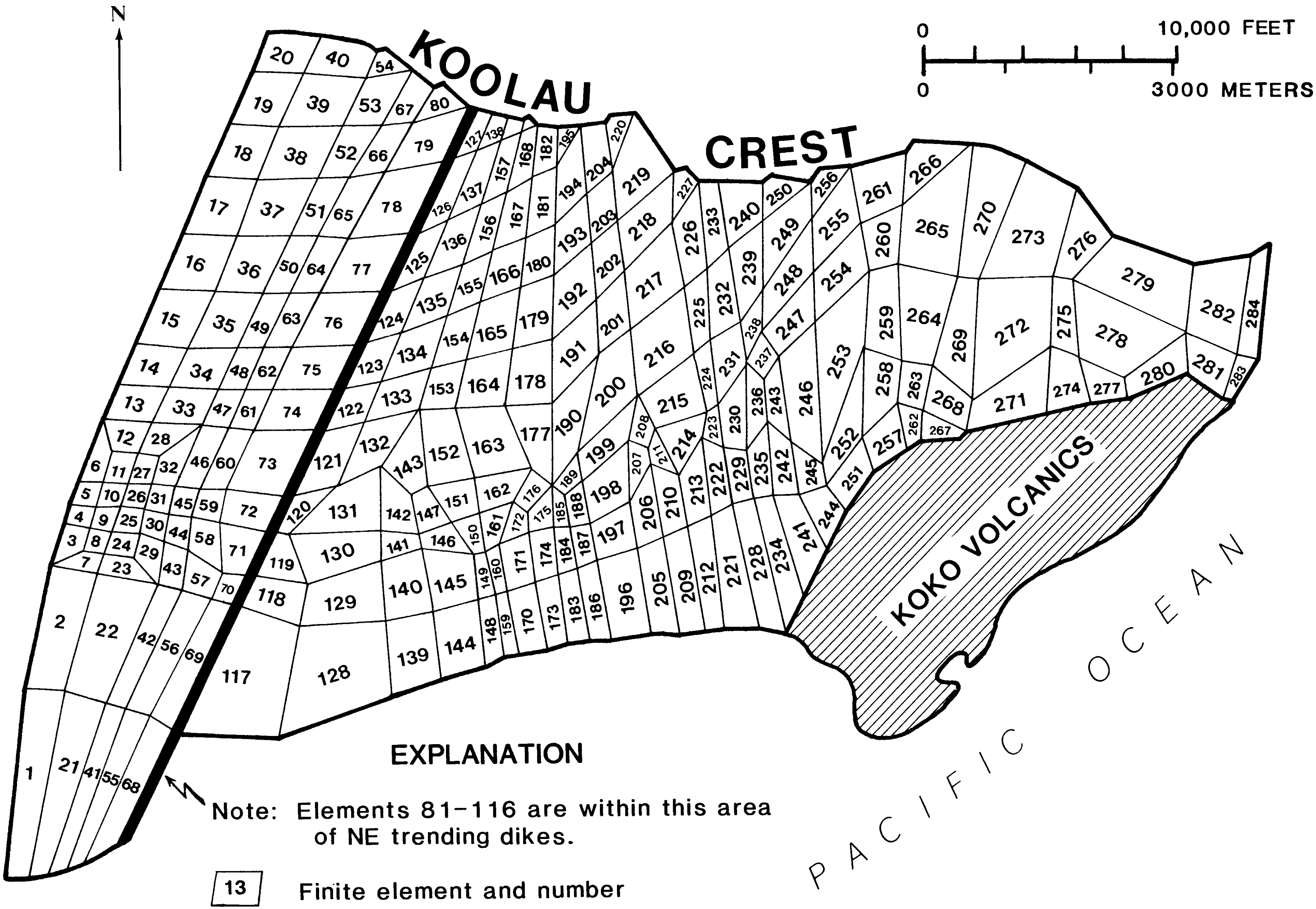


Figure 14. Finite-element mesh for leeward southeast Oahu.

Runoff

To calculate mean monthly runoff from each element, first the mean annual runoff for each drainage basin in the study area was calculated. Using data from gaged leeward basins in Hawaii with 10 or more years of continuous record, Matsuoka (U.S. Geological Survey, written commun., 1983) derived a multiple regression equation that estimates mean annual basin runoff from mean annual basin rainfall, drainage area, stream slope, and percent forest cover. The equation is:

$$\log Q = -5.30 + 1.84 (\log P) + 0.669 (\log D.A.) + 0.814 (\log S) - 0.331 (\log F.C.) \quad (4)$$

where:

Q = mean annual runoff in cubic feet per second

P = mean annual precipitation in inches

D.A. = drainage area in square miles

S = stream channel slope in feet per mile

F.C. = percent forest cover

log = logarithm to the base 10

An annual rainfall-runoff relationship for southeastern Oahu was established by fitting a power curve, of the form $y = ax^b$, through a plot of mean basin runoff versus mean basin rainfall (fig. 15). A least squares fitting procedure yielded the equation:

$$\text{Runoff} = 0.00173 \times \text{Rainfall}^{2.06153} \quad (5)$$

(the coefficient of determination, $R^2 = 0.77$).

This equation was applied to the rainfall of each element of the grid, producing annual runoff in inches for each element.

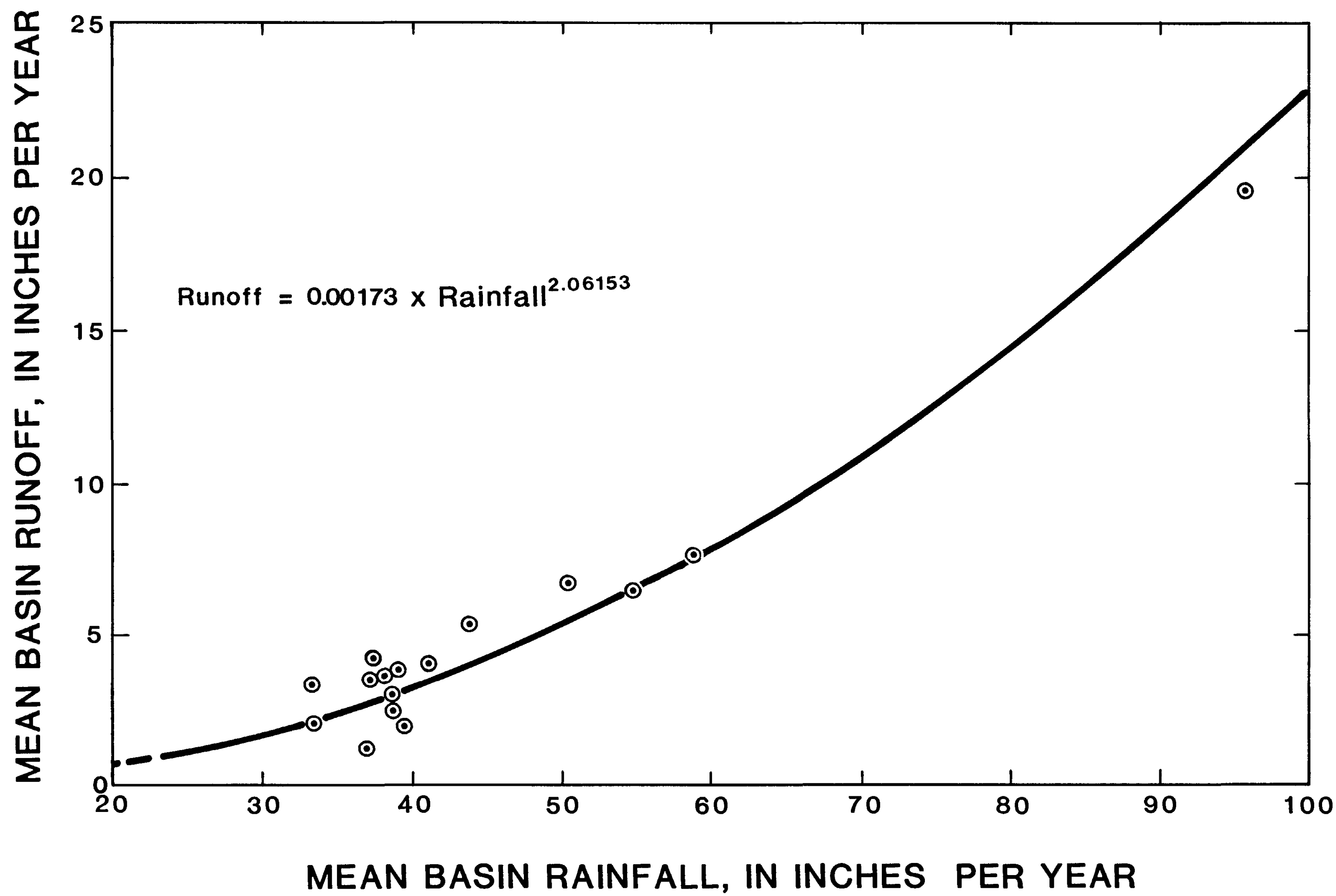


Figure 15. Rainfall-runoff relationship for leeward southeast Oahu.

To check that the total basin runoff had not been altered by applying the power curve relationship to each element, the sum of runoff from elements in a basin was compared to the basin's runoff calculated from equation 4. The difference in basin runoff calculated by the two methods ranged from +1.5 to -1.6 in./yr for 16 basins in the study area. The mean difference was .002 inches which indicates that basin runoff calculated per element was not significantly different from the runoff calculated for the whole basin. Monthly runoff per element was calculated by multiplying annual runoff by the ratio of the element's monthly to annual rainfall. In this way seasonal fluctuations were introduced into the runoff component of the water budget calculations.

The mean annual runoff from the study area, calculated by equation 5, is 6.4 Mgal/d; 3.5 Mgal/d (9 in./yr) from the Waialae area and 2.9 Mgal/d (4 in./yr) from the drier Wailupe-Hawaii Kai area.

Potential Evapotranspiration

A large fraction of rainfall is evaporated and transpired back to the atmosphere. Estimates of potential evapotranspiration, "water loss from a large homogeneous, vegetation-covered area that never suffers from a lack of water" (Mather, 1978), can be made by an energy budget of solar radiation data.

Under optimum soil-moisture conditions, and if advected energy is negligible, potential evapotranspiration (PE) may equal net radiation. Net radiation is defined as the incoming long- and short-wave radiation from the sun, minus reflected radiation and outgoing long-wave radiation from the earth (Mather, 1978, p. 4). Therefore:

$$\text{PE} = \text{net radiation} = \text{global radiation} - (\text{reflectance})(\text{global radiation}) + \text{actual net long-wave radiation} \quad (6)$$

where:

Global radiation = mean annual incoming long- and short-wave radiation (fig. 16)

Reflectance = the fraction of global radiation that is reflected by the earth, approximately 10 percent for Oahu (Ekern, 1965)

Actual net long-wave radiation = (clear-day net long-wave)(global radiation/clear-day global)

Clear-day net long-wave = approximately -150 $cal/cm^2/d$ (calories per $centimeter^2$ per day) (Charnell, 1967)

Clear-day global = 0.8 Angot value for 20° north latitude (Yoshihara and Ekern, 1978)

Angot value = the amount of incoming solar radiation at the top of the atmosphere

Using these equations, equation 6 can be rewritten:

$$PE = \left[(1 - 0.1)(\text{global radiation}) + \frac{-150 \times \text{global radiation}}{0.8 \times \text{Angot value at } 20^{\circ}\text{N}}\right]\left(\frac{30}{1{,}485}\right) \quad (7)$$

Global radiation, from figure 16, was converted to units of $cal/cm^2/d$ by dividing $watts/m^2$ (watts per square meter) by 2.06. Because there are about 30 days in a month, and 1,485 cal/cm^2 are required to evaporate an inch of water, the factor 30/1,485 converts units of $cal/cm^2/d$ to inches of water per month.

Ekern (1983) has shown that PE can be calculated from the Priestley-Taylor relationship (1972), which for Hawaiian conditions indicates that PE is about 0.9 times net radiation. Owing to the uncertainties in the data required to calculate both net radiation and the Priestley-Taylor factor, setting PE equal to net radiation, as in equation 6, is an acceptable approximation.

Annual global radiation per element was obtained by transferring values from figure 16 to each element. Monthly global radiation was calculated by multiplying mean annual global radiation by the 12 ratios of mean monthly to mean annual radiation determined at Makiki Agriculture Station No. 707, 1.5 miles northwest of the study area (How, 1978). Monthly Angot values were obtained from Chang (1971).

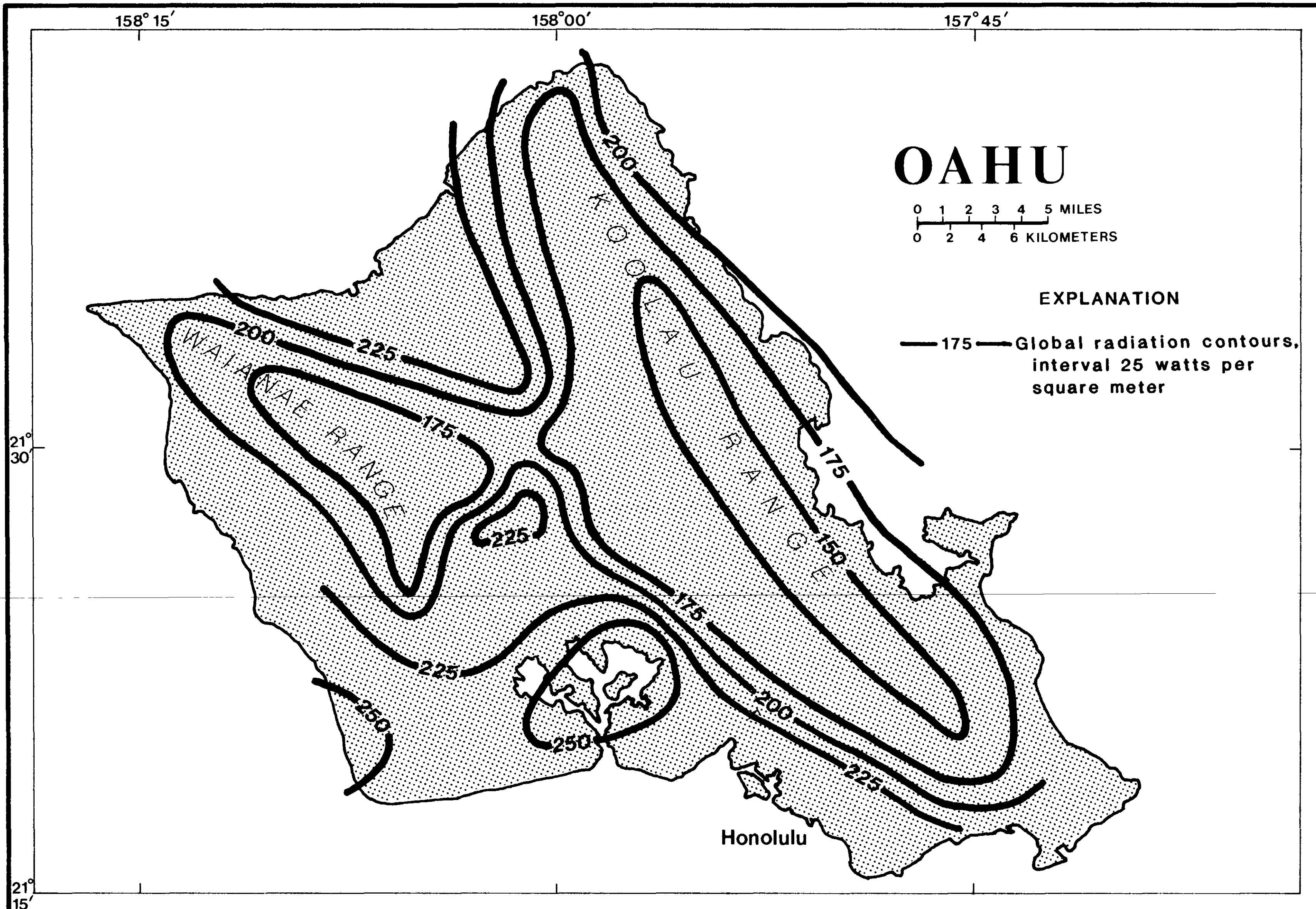


Figure 16. Mean annual global radiation over Oahu in watts per square meter (from Ramage, 1979).

Equation 7 provided the values of potential evapotranspiration for equation 3. Estimates of actual evapotranspiration, one of the results from the use of equation 3, may be less than potential evapotranspiration. This occurs because the rainfall for a given month may not be sufficient to supply the full amount of potential evapotranspiration.

Mean annual evapotranspiration in this relatively dry and sunny area of Oahu was 35.5 Mgal/d; 14.5 Mgal/d (38 in./yr) from the Waialae area and 21 Mgal/d (29 in./yr) from the Wailupe-Hawaii Kai area. Even though solar radiation is greater, the actual rate of evapotranspiration (in units of in./yr) is less in the drier Wailupe-Hawaii Kai area than in the Waialae area because low rainfall limits the amount of water available for evapotranspiration.

Soil Characteristics

To calculate the term "change in soil storage" in the water budget equation, the amount of water the soil can store must be known. This amount, called maximum soil storage in this report, is equal to the available water in the soil (field capacity minus wilting point) multiplied by the depth of the vegetation root zone. Water content in excess of field capacity will drain from the soil and recharge the aquifer. Water content less than wilting point will be held in the soil unavailable for evapotranspiration.

Because much of southeast Oahu has received only a reconnaissance soil survey, available water and plant root depth were estimated. These estimates were based on data from Foote and others (1972), field trips to the area, and discussions with soil-survey personnel. Values of available water ranged from 0.1 to 0.15 inch per inch of soil. Plant root depth ranged from 4 to 10 inches in mountainous areas where bedrock is near or at the surface and from 2 to 4 feet in alluvial areas where vegetation is more dense.

Based on the soil survey, approximately 10 different soil types were assigned to the 284 elements of the finite-element mesh. Although the values of soil storage are approximate, the relatively fine discretization of soil types across the area enabled the effects of variable soil properties to be incorporated into the calculation of recharge.

Calculation of Recharge

Having quantified the components of the water budget equation, equation 3 is solved for monthly values of recharge for each element of the mesh in the following way:

1) Runoff is subtracted from rainfall and the difference is added to soil storage.
2) If the resulting soil storage is greater than the maximum soil storage, the excess is set equal to recharge and soil storage is set equal to maximum soil storage. If the resulting soil storage is less than maximum soil storage, no recharge occurs.
3) Potential evapotranspiration (PE) is subtracted from soil storage. If PE is greater than soil storage, PE is set equal to soil storage, and soil storage goes to zero. In this way, actual evapotranspiration is estimated. An annual water budget would not be able to correct for the difference between potential and actual evapotranspiration.
4) Repeat the process for the next month.

Commonly, steps 2 and 3 of the preceding calculation are reversed, allocating water to evapotranspiration before recharge occurs. Allowing recharge to occur first, as was done for this report, seems more correct in this case, for two reasons. First, recharge occurs mainly during storms, when rainfall intensity is high and evapotranspiration is low. Second, the saturated infiltration rate through these soils is on the order of feet per day, whereas the rate of evapotranspiration is on the order of feet per year. Therefore, during and after storms, much of the soil water infiltrates past the root zone before it can evaporate back to the atmosphere.

Mean annual recharge was calculated by summing monthly recharge. Monthly and annual recharge by element are presented at the end of the report. The foregoing process yielded 15.1 Mgal/d of recharge through the study area (table 3). This value is 26 percent of the total rainfall of 57 Mgal/d (51 in./yr). Of the 15.1 Mgal/d, 6 Mgal/d (16 in./yr) recharges the Waialae area and 9.1 Mgal/d (12 in./yr) recharges the Wailupe-Hawaii Kai area. Present pumpage from the Waialae and Wailupe-Hawaii Kai areas is 1.2 and 0.2 Mgal/d, respectively.

The calculation of ground-water flow through the Waialae area, using Darcy's law, yielded a value of 5.5 Mgal/d. Values of 6.7 and 10.1 Mgal/d were calculated for the Wailupe-Hawaii Kai area depending on whether hydraulic conductivities of 1,000 or 1,500 ft/d were used.

Table 3. Water balance for leeward southeast Oahu

Area	Rainfall		Runoff		Evapotrans-piration		Recharge	
	Mgal/d	in./yr	Mgal/d	in./yr	Mgal/d	in./yr	Mgal/d	in./yr
Waialae ($8.1\ mi^2$)	24	62	3.5	9	14.5	38	6.0	16
Wailupe-Hawaii Kai ($15.3\ mi^2$)	33	45	2.9	4	21.0	29	9.1	12

GROUND-WATER SIMULATION

Conceptual Model

The western part of the study area, the Waialae area, is bounded on the north, east, and west by dike intrusions and on the south by coastal sediments (caprock) that are significantly less permeable than basalts. Ground-water recharges the aquifer principally in the highlands where rainfall is greatest. The low permeability of the dikes provides a barrier to lateral movement of ground water which causes most of the ground water to discharge through the caprock as diffuse leakage along the coast. Water-level records confirm that ground water flows principally from north to south, and show that the caprock inhibits free discharge of ground water to the sea, creating 8- to 10-foot heads near the caprock-basalt contact.

Though there may be some leakage of ground water from Waialae to Wailupe-Hawaii Kai, the abrupt head drop between the two areas indicate that the dike boundary is poorly permeable and leakage is probably small. The total ground-water flow through the 8.1-mi^2 Waialae area is about 6 Mgal/d, or about 4 Mgal/d per mile width of aquifer.

The hydrologic boundaries of the Wailupe-Hawaii Kai area, east of the Waialae area, are the dikes of the Koolau rift zone to the north, the northeast-trending dike divide on the west (Takasaki and Mink, 1982) and the caprock discharge boundary on the south and east. A thin lens of freshwater has formed as a result of the combined effects of lower rainfall and more permeable coastal sediments than in the Waialae area. Wells drilled near the coast produce brackish water. Two wells drilled more than a mile inland tap a freshwater lens having 3- to 4-foot heads. Heads in this area decline to the east as rainfall declines, and to the south as the lens discharges to the sea. Ground-water flow through the 15.3-mi^2 Wailupe-Hawaii Kai area is about 9 Mgal/d, or about 1 Mgal/d per mile width of aquifer.

The Ghyben-Herzberg relation states that a static freshwater lens (with density = 1.0 grams/cm^3), floating on seawater (with density = 1.025 grams/cm^3), will have a thickness equal to about 41 times the head of freshwater above sea level. Several deep monitor wells in Hawaii show that the thickness of a lens may be closely predicted by the relation, or in error up to plus or minus 20 percent. The 10 foot heads in the Waialae area indicate that the thickness of the freshwater lens is about 400 feet. Three-foot heads in the western part of the Wailupe-Hawaii Kai area suggest that the thickness is about 120 feet, becoming thinner so that brackish water predominates in the southern and eastern parts.

Mathematical Model

Computer programs that simulate the flow of groundwater solve the groundwater flow equation for the specific conditions of the user's problem. The ground-water flow equation, Eq. 8, represents the combination of the conservation of mass equation with Darcy's law. The conservation of mass states that the change of storage that occurs within a certain control volume equals the amount of water that flows into the volume minus the amount that flows out. Given a flow rate that satisfies the conservation of mass, then the water table must have a slope that is consistent with Darcy's law. When the equation of the conservation of mass and Darcy's law are coupled for a water-table problem in two-dimensions, the ground-water flow equation is (Voss, 1984a):

$$S \frac{\partial h}{\partial t} = \frac{\partial}{\partial x}\left(\lambda \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda \frac{\partial h}{\partial y}\right) + Q + Q_L \qquad (8)$$

where:

$h = h(x, y, t)$ is the hydraulic head in the freshwater body (L)

$S = S(x, y)$ storage coefficient of the aquifer (dimensionless)

λ = is transmissivity $T(x, y)$ for portions of the aquifer confined both above and below, or (L^2/T)

= product of hydraulic conductivity and aquifer thickness, $Kb\ (x, y, t)$, for aquifer portions unconfined either above or below.

$K = K(x, y)$ is the hydraulic conductivity of the aquifer (L/T)

$b = b(x, y, t)$ is the saturated freshwater thickness of the aquifer (L)

$Q = Q(x, y)$ is the strength of a source function, that is: volume of the freshwater per time added per horizontal area of the aquifer $(L^3/T)/(L^2$ aquifer) (L/T)

$Q_L = Q_L(x, y, t)$ is the strength of leakage into the freshwater body that is: volume of freshwater leakage into the aquifer per time and per horizontal area of aquifer $(L^3/T)/(L^2$ aquifer) (L/T)

x, y = coordinate directions

t = time (T)

Q_L is a steady leakage through a semi-confining bed, and is defined as:

$$Q_L = -\left(\frac{K_1}{B_1}\right)(h - h_o) \tag{8a}$$

where:

$\left(\frac{K_1}{B_1}\right)$ is called the leakance of the confining bed

K_1 = the hydraulic conductivity of the confining bed (L/T)

B_1 = the thickness of the confining bed (L)

h_o = the hydraulic head on the side of the semi-confining bed opposite the aquifer

For flow out of an aquifer, through a semi-confining bed like the caprock, Q_L is negative.

This study used the finite-element program, AQUIFEM-SALT (Voss, 1984a), developed as a modification to the program AQUIFEM (Pinder and Voss, 1979). Voss modified the aquifer-thickness and storage terms in AQUIFEM to incorporate the Ghyben-Herzberg ratio into the model so that it could be used for situations where a freshwater lens floats on seawater. Essentially, thickness was set equal to 41 times the head, and changes in storage were calculated as 41 times the change in head times the specific yield. Also, the free-floating lens may be truncated above or below to a thickness of less than 41 times the head by a confining unit such as the caprock.

The relationship of 41 to 1 between the lens thickness and head is true only when the lens is at equilibrium. In reality, the water table continually fluctuates in response to changes in rainfall and pumping conditions, but the motion of the bottom of the lens is more sluggish and responds to the flow fields of both the freshwater and the underlying saltwater. The location of the lens bottom is more accurately predicted by the water-table elevation averaged over a time span of several years rather than by any instantaneous measurement of the water-table elevation. Such a deficiency does not affect the value of the model when used to describe the equilibrium freshwater flow system and distribution of heads. However, head values resulting from short-term transient simulations may contain some error.

Model Application and Calibration

Using input data of aquifer characteristics and recharge rates, the computer model calculates ground-water heads at each node of the finite element-mesh presented in figure 14. Nodes are located at the intersection of element boundary-lines. Ground-water flow in the Koko Volcanics was not simulated because those volcanics form a brackish-water aquifer separate from the Koolau basalt aquifer (Takasaki and Mink, 1982). The western and northern perimeters are modeled as no-flow boundaries simulating the dikes of the Kaau rift zone and the Koolau Range. Along the eastern and southern boundaries, the caprock is treated as a leaky confining layer through which water discharges upward to the sea at a rate proportional to the head in the underlying basalt aquifer. The northeast-trending dikes, which act as a barrier between the Waialae and Wailupe-Hawaii Kai areas, are simulated by narrow elements with a low hydraulic conductivity of 0.1 ft/d.

Soroos (1973) analyzed many pumping tests and obtained hydraulic conductivities of flank flows of Koolau basalts that ranged from 300 to 2,000 ft/d and averaged 1,100 ft/d. After several trial simulations the hydraulic conductivity (K) of the Waialae area was selected to be 500 ft/d. This value corresponds well to the value of 400 ft/d obtained from the Waialae shaft pumping test, is reasonable for flank flows of Hawaiian volcanoes that are sparsely intruded by dikes, and produced simulations that were in closest agreement with the observed ground-water gradient. A hydraulic conductivity of 800 ft/d for the Wailupe-Hawaii Kai area provided the best simulation results for that area.

Other model input data were chosen as follows: Thornthwaite and Mather's (1955) water-budget approach was used to calculate recharge for each element of the mesh. Withdrawal at a pumping node was set at the long-term-average-pumping rate of the well at that node. Mink (1980) shows that the specific yield for Koolau basalt aquifers is between 0.02 and 0.14. A value of 0.1 was used in the long term simulations presented in this report. Assigned caprock leakance (hydraulic conductivity of the caprock/thickness of caprock) ranged from a low of 0.0004 per day in the coastal Waialae area to a high of 0.02 per day in the coastal Hawaii Kai area.

The leakance assigned to the confining elements determined the ease with which water could escape from the aquifer to the sea. A low value of leakance caused heads to build up in the aquifer. A high value allowed water to escape more easily, creating lower heads in the aquifer. The spatial variation in leakance simulates the decrease in caprock effectiveness between the western and eastern parts of the study area. The changing of leakance values was the principal adjustment used to obtain good agreement between observed and simulated heads.

The leakance of 0.0004 per day corresponds to a section of caprock about 800 feet thick, with hydraulic conductivity of 0.3 ft/d. These are reasonable values for the area around Diamond Head. The leakance of 0.02 per day corresponds to a section of caprock about 50 feet thick, with hydraulic conductivity of 1 ft/d. These are reasonable values for the coastal sediments of the Wailupe-Hawaii Kai area.

The model only accepts 1 value of hydraulic conductivity for the leaky confining elements. To achieve the desired leakances, a hydraulic conductivity of 0.3 ft/d was used and the thickness of each confining element was set as presented in figure 17.

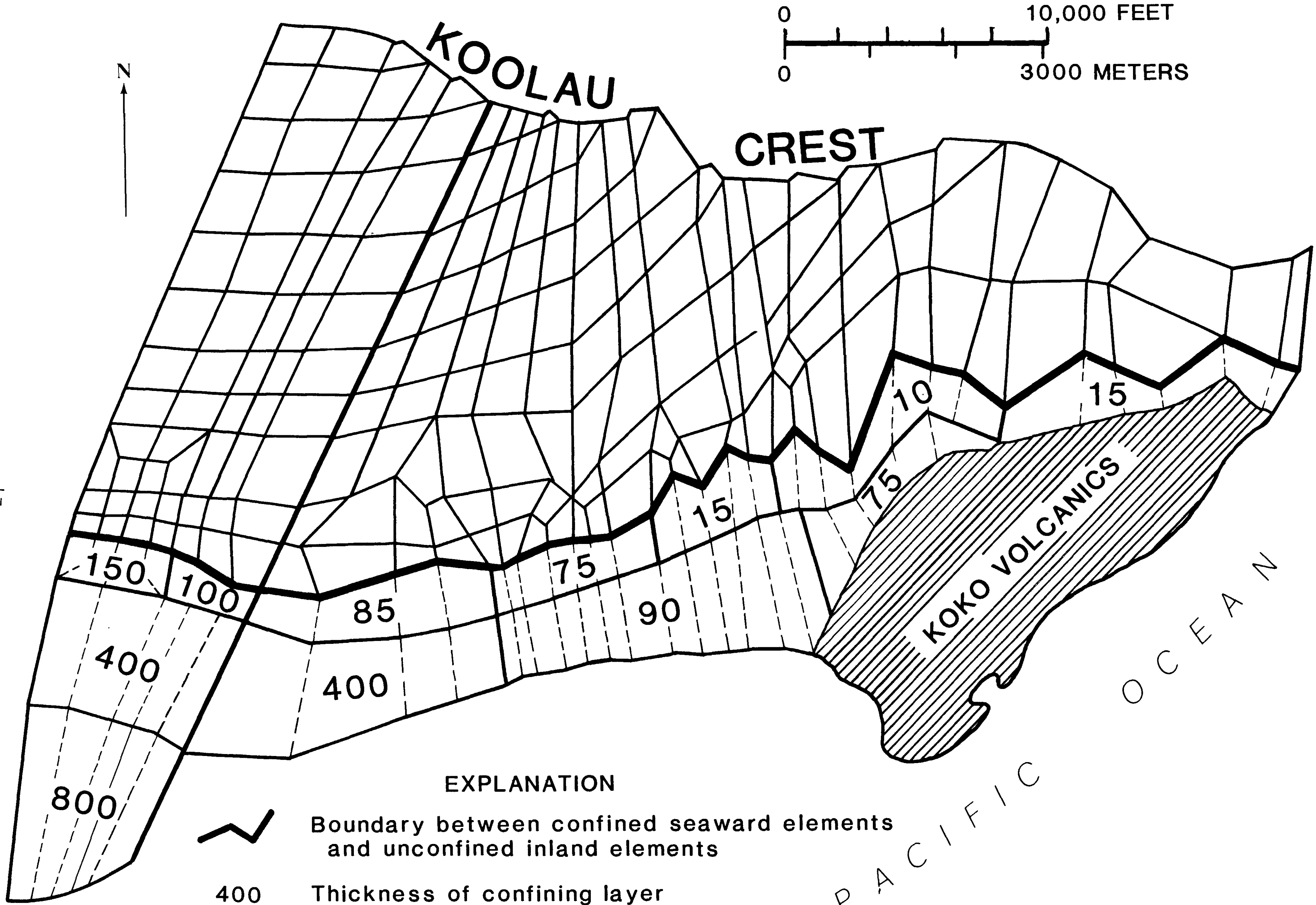


Figure 17. Finite-element mesh for leeward southeast Oahu showing the thickness of the confining layer.

Because leakance is the least known variable in the model, it is appropriate that significant adjustments be made to obtain close agreement between observed and simulated heads. Hydraulic conductivity is a better known variable and it was adjusted only within a narrow range. Recharge was not adjusted at all from the values obtained from the water budget, except for short term simulations that investigated fluctuations in head that result from wet or dry years.

Data from several wells provide a distribution of heads across the study area that can be compared to the simulated results (tables 4 and 5, and figure 18). The close agreement between simulated and observed heads shows that the model has been adequately calibrated. Most of the historic head data were obtained after the initiation of pumping from the Waialae golf course well (node 76) and Waialae shaft (node 41). The observed head data reflect area-wide drawdown, and therefore simulations for head calibration included pumpage from those two sources.

An equally good fit between simulated and observed heads, as presented in table 4, was achieved by increasing hydraulic conductivity of the northeast-trending dike zone from 0.1 to 1 ft/d, thus allowing about 2 Mgal/d to leak eastward across the barrier. The drop in Waialae area heads caused by this loss of water was compensated for by decreasing the caprock leakance in the Waialae area.

This sensitivity analysis shows that despite a good simulation of observed heads, all uncertainties in the flow system cannot be resolved. Because the western and eastern barriers of the Waialae area are similar in nature, outflow across the eastern boundary, if any, will nearly be equalled by inflow from the west. Therefore, flow across these boundaries was fixed near 0 Mgal/d.

Table 4. Distribution of heads in leeward southeast Oahu

Node number (shown on figure 18)	41	45	62	76	78	144	163	206	237	277	316	317
Observed head, (ft)	9.6	11.5	10.6	8.5	9.5	2.7	3.7	2.2	3.7	0.8	1.3	2.2
Simulated head, (ft)	9.7	11.2	10.4	8.2	10.2	2.8	3.8	2.4	3.8	0.4	1.4	2.4

Table 5. Cross reference of node numbers and well identification

Node number	USGS number	Name or location
41	1747-02	Waialae shaft
45	1747-03	Waialae nui
62	none	Drill hole 23
76	1646-01, 02	Waialae Golf Course
78	1746-01	Aina Koa
144	1746-02	Waialae Iki
163	1745-01	Wailupe
206	1744-01, 02	Niu Valley
237	1843-01	Kuliouou valley
277	1842-01	Kamilonui valley
316	1840-01	Kalama valley
317	1840-04	Kalama valley

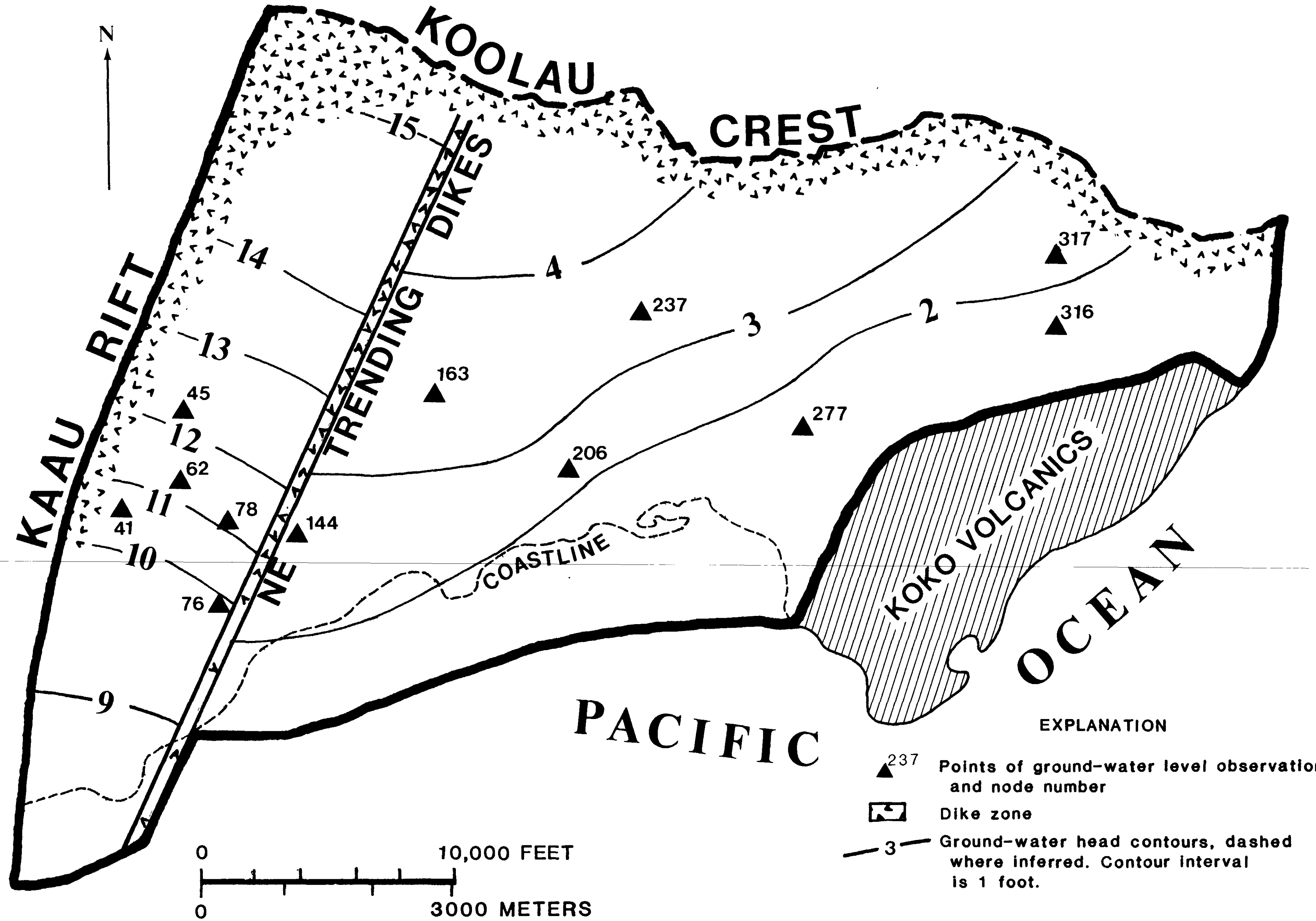


Figure 18. Simulated pre-pumping ground-water head distribution in leeward southeast Oahu.

Effects of Pumping on the Pre-pumping Head Distribution

Initial heads in the study area were simulated by eliminating pumpage in the calibrated data set and running the simulation until heads stopped rising and reached a steady state (fig. 18). The history of head changes was then simulated by running the model and adding pumpage at the proper time. The Waialae golf course well (node 76) began pumping at a rate of 0.35 Mgal/d in 1881, Waialae shaft (node 41) at 0.42 Mgal/d in 1937 and the Aina Koa well (node 78) at 0.42 Mgal/d in 1971. Figure 19 shows the simulated head distribution in 1971. A graph of simulated and maximum annual observed heads from 1935 to 1975 at the Waialae shaft is presented in figure 20. Minimum annual heads track less than 0.5 feet below maximum annual heads.

It was suspected that the fluctuations in observed water levels shown in figure 20 were caused by varying recharge rates from years of high and low rainfall. To test this idea, the difference between simulated annual heads resulting from constant recharge, and observed heads was analyzed by comparing their differences with the smoothed differences between observed and mean annual rainfall in the area. This comparison is shown in figure 21. The best correlation ($R^2 = 0.89$) between the two sets of differences, obtained by a linear least-squares method, was achieved with a centered three-year moving average of the rainfall differences, lagged one year with respect to the water-level differences. Figure 21 shows that where large seasonal pumping stresses do not occur, as in the study area, fluctuations in head can be explained by fluctuations in rainfall. The statistical correlation shows that about one year is required for the effects of recharge to be transmitted from the ground surface to the water table. This lag may be in error by several months, because lag times of about one year cannot be accurately determined using annual data.

Transient simulations of short term ground-water head fluctuations are desired because the improved understanding of lens behavior will allow pumping rates to be better managed. Also, to the extent that ground-water head reflects the position of the freshwater-saltwater interface, a more detailed knowledge of head fluctuations will allow the chloride distribution through the lens to be estimated.

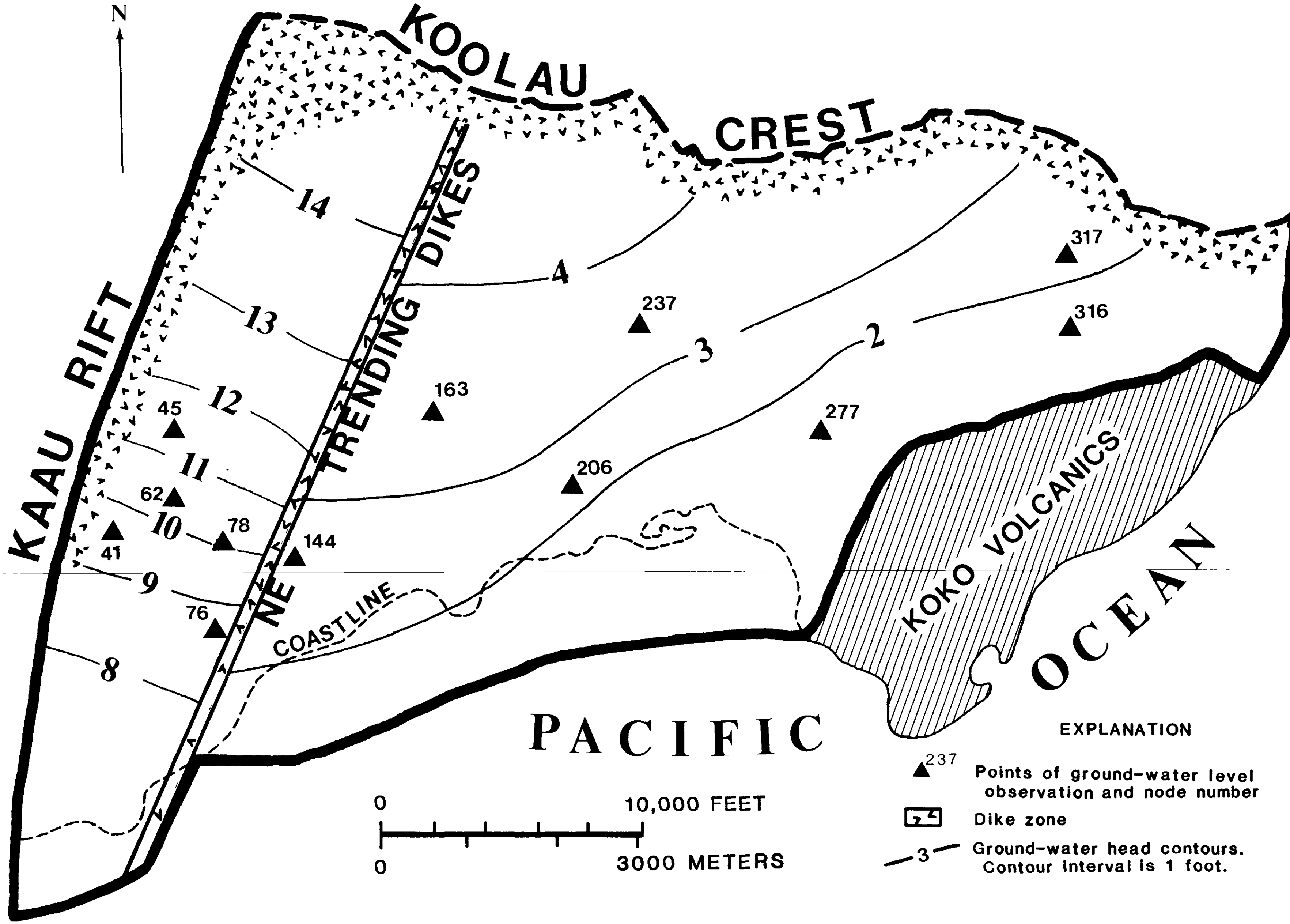


Figure 19. Simulated ground-water head distribution in 1971 as a result of Waialae shaft (node 41) and golf course well (node 76) pumpage.

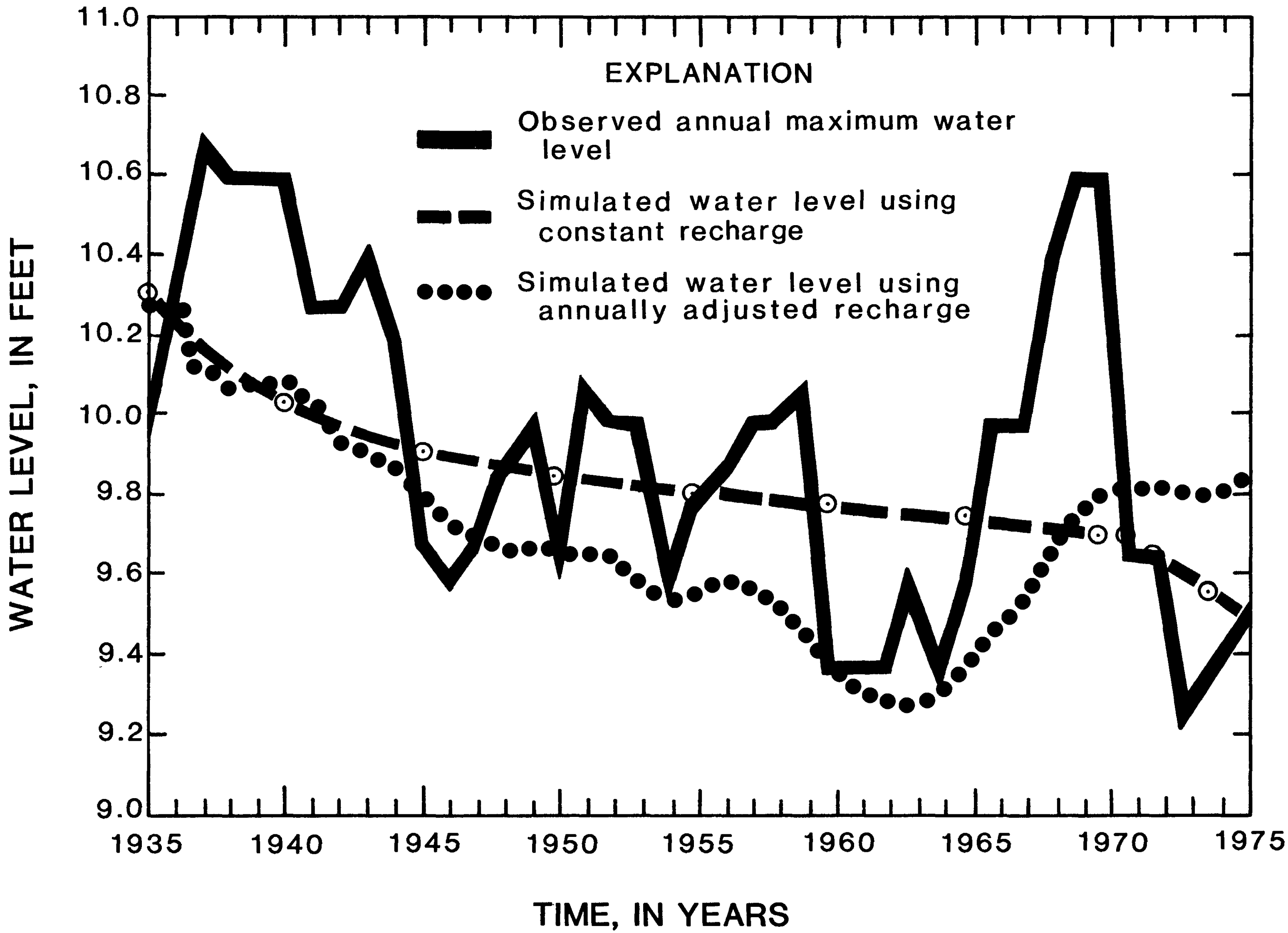


Figure 20. Simulated versus observed heads from 1935 to 1975 at the Waialae shaft (node 41) Specific yield = 0.10.

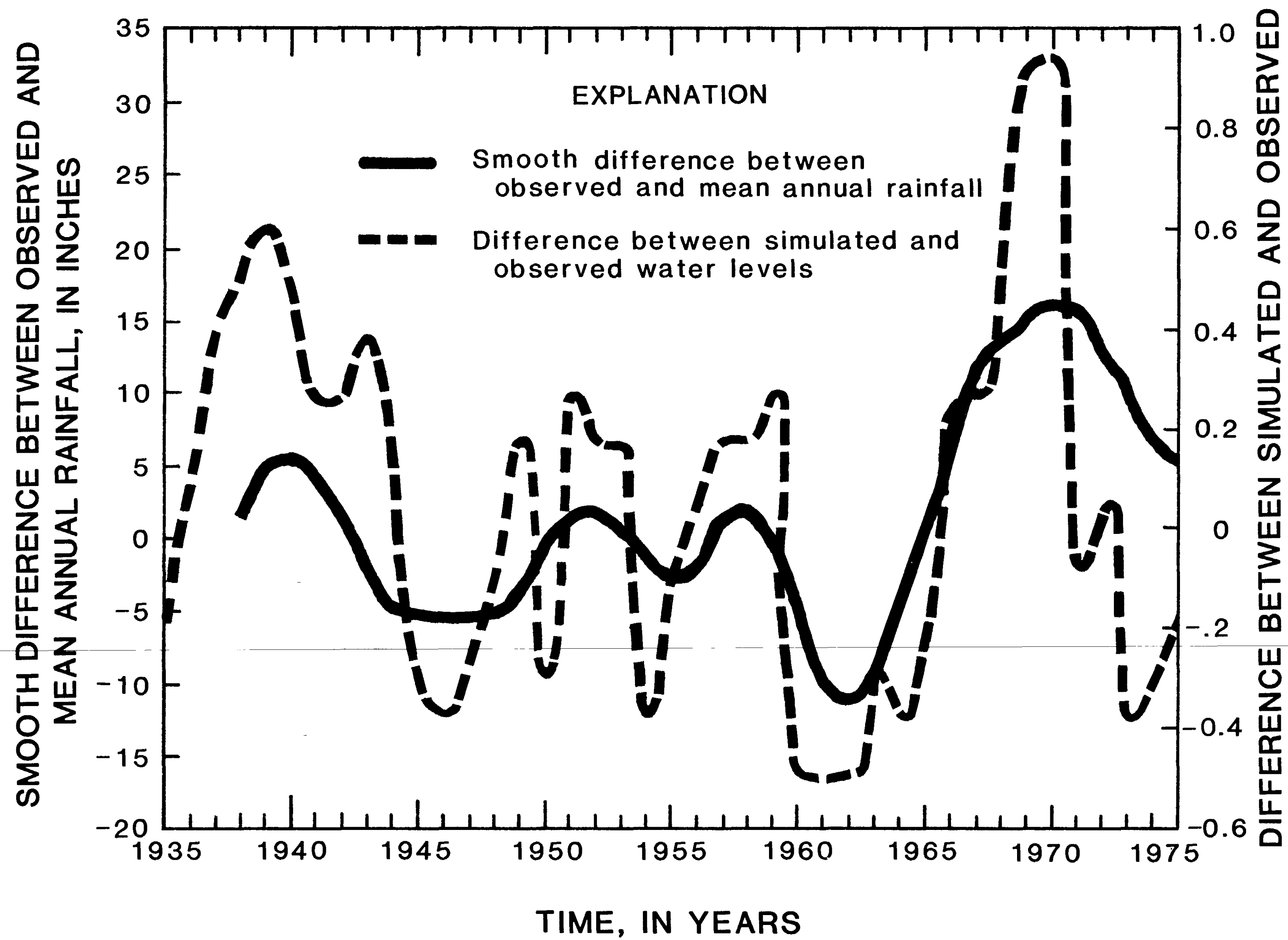


Figure 21. Differences between observed and mean annual rainfall, and between simulated and observed heads.

In an attempt to simulate the annual fluctuations of the water table, new recharge data sets were recalculated annually from fluctuations in rainfall. However, simulated head values are consistently low by a few tenths of a foot. The model was calibrated using long term mean recharge, and therefore, during the dry years, 1935 to 1962, annual simulations produce low heads. During the wet years, 1963 to 1975, simulated heads rise and become greater than observed heads.

Also, the simulated fluctuations shown in figure 20 do not match the observed fluctuations particularly well, especially the higher frequency fluctuations. A possible source of this error is the inherent limitation of a two-dimensional plan-view model which assumes hydrostatic equilibrium of fresh and salt water. The problem of simulating high-frequency water-level fluctuations revolves around the relationship between changes in water volume in the aquifer and associated changes in head. This relationship is dependent on the storage of the aquifer.

The model uses a storage coefficient that is 41 times greater than the specific yield of the aquifer because, at equilibrium, a one-foot rise in the water table will cause the bottom of the lens to move down 40 feet. The volume of water associated with these changes will be distributed accordingly. Initially, after the water table rises from a slug of recharge, the bottom of the lens has not had time to fully readjust. Therefore, the lens is not in equilibrium, the storage coefficient of 41 times the specific yield is too large, and simulated head changes are smaller than observed. This may be occuring in the present simulations.

Better simulations can be obtained by decreasing the storage coefficient by reducing the specific yield (fig. 22). The amount of adjustment in specific yield required to obtain a good simulation may, in view of the equilibrium assumption, reflect the amount of disequilibrium in the lens. The required adjustment would change depending on the time scale of the fluctuations.

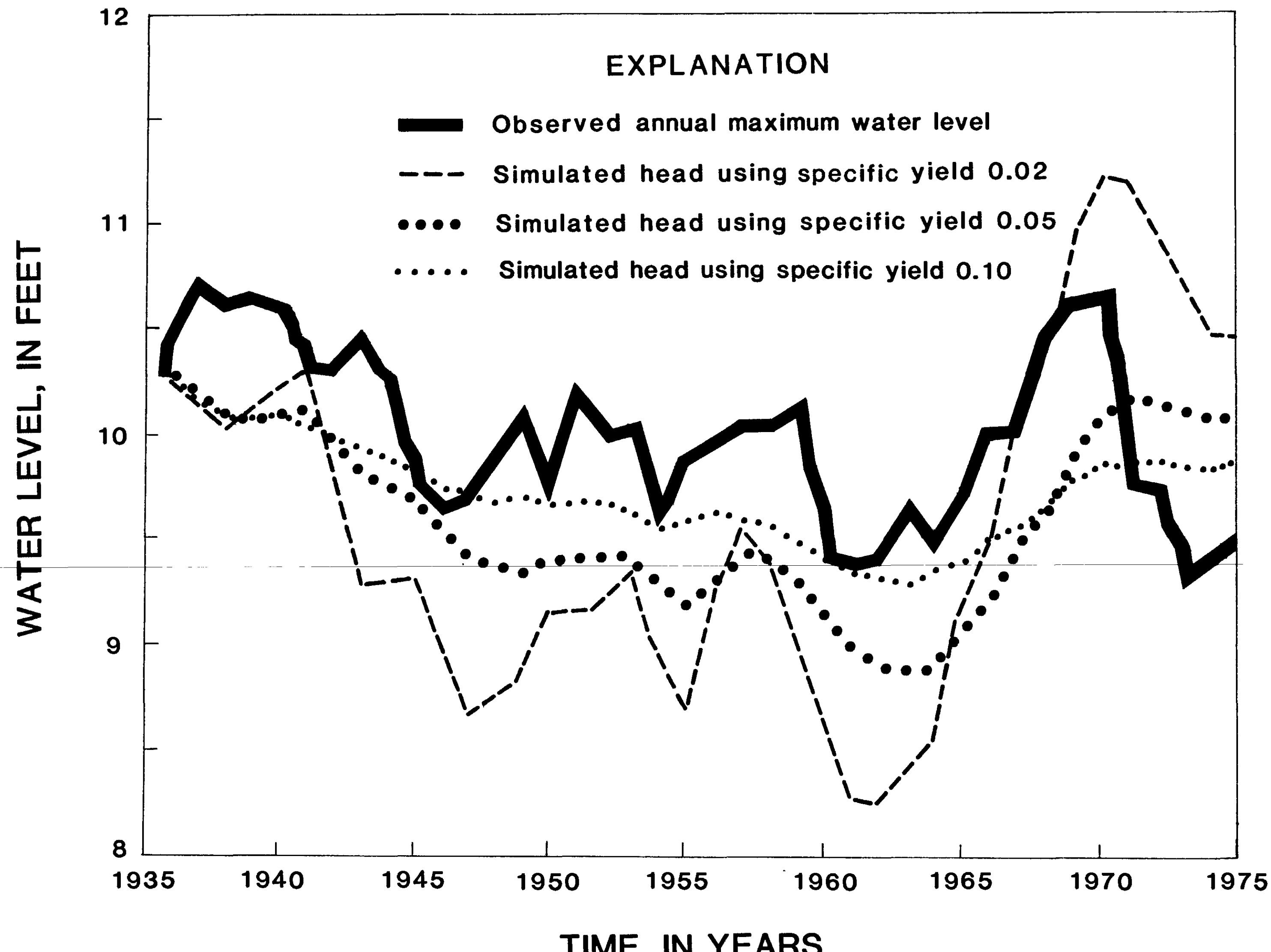


Figure 22. Simulated water levels using annually adjusted recharge and specific yields of 0.10, 0.05, and 0.02.

The variation in response resulting from different specific yield values, ε, is shown in figure 22. As is expected, the lower values of ε allow better simulation of the higher frequency components of head change. The lower values of specific yield, $\varepsilon = 0.02$ and $\varepsilon = 0.05$, are, in fact, reasonable values and are within the present range of uncertainty for Koolau basalts. Thus, another uncertainty in model calibration arises because it is not possible to determine from available data how much model error is due to the equilibrium assumption and how much is due to the particular choice of a specific yield value. Of course unavoidable error in recharge data also limit the accuracy of short term simulations.

In one sense the "equilibrium-specific yield dilemma" is not a serious problem. The model is able to predict a new 'steady-state' head distribution across the aquifer given a new set of pumping or recharge conditions no matter what specific yield is used because the 'steady-state' heads do not depend on specific yield. However, both the time it takes to achieve 'steady-state' and the magnitude of water-table fluctuations are dependent on the specific yield. With a low specific yield, 'steady-state' will occur sooner and fluctuations will be greater than with a larger specific yield.

The unfortunate consequence of the "equilibrium-specific yield dilemma" is that the location of the freshwater-saltwater interface cannot be predicted with much accuracy. Inaccuracy in the location of the interface, where chloride concentration is about 10,000 mg/L (milligrams per liter), makes estimation of the chloride distribution through the ground-water lens subject to excessive error.

Model Predictions

Recently-drilled wells at nodes 45, 163, and 237 will be put into production within the next two years. The effect on ground-water heads was predicted by adding pumpage of 0.2 and 0.4 Mgal/d from each of these new sources to the simulations previously discussed. Figure 23 shows the simulated history of heads at the Waialae golf course well and Waialae shaft, including the projected effects of new pumping. Water levels in the Waialae area will drop about a foot from their present mean position as a result of continued drawdown from present pumpage as well as additional drawdown from projected pumpage. These curves result from using a specific yield of 0.10. As stated earlier, the curves would be steeper and level off sooner if a smaller specific yield had been used. However, the equilibrium head which occurs when the curve stops declining, would be the same as those shown in figure 23. Figure 24 shows the projected head distribution over the study area resulting from a pumping rate of 0.2 Mgal/d at the new sources. A rate of 0.4 Mgal/d lowers the head an additional 0.2 foot. Water levels in the Wailupe-Hawaii Kai area will drop about 0.5 foot in the eastern part and essentially no change will occur in the western part.

Water Quality

Contamination by saltwater upconing is the major water-quality concern in southeast Oahu. The computer simulation done for this study addressed long-term water-level changes resulting from present and future pumping, from which water-quality changes can only be inferred. Figure 25 shows the dependence of chloride concentration on rainfall and pumpage. Figure 20 shows corresponding fluctuations in water levels. From 1955 through 1959 rainfall declined and pumpage was reduced slightly, and the chloride concentration of water pumped from Waialae shaft was relatively constant, ranging from 130 to 160 mg/L. In 1960, as rainfall increased, pumpage was increased to 246 Mgal for the year. This large volume of pumpage, combined with the probability that the ground-water lens had not recovered from the previous period of low rainfall, caused the chloride concentration to rise to 200 mg/L in late 1960 and early 1961.

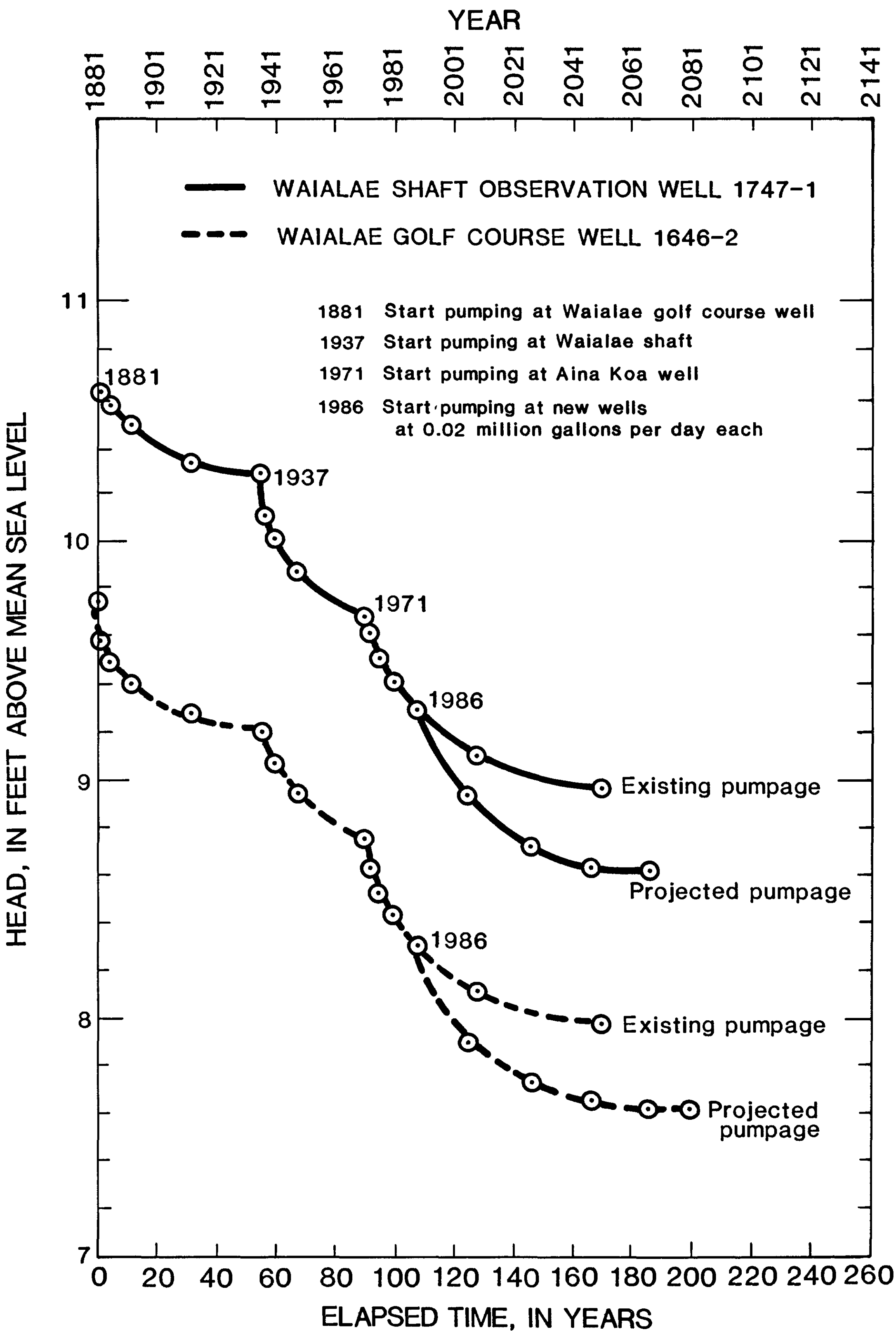


Figure 23. Simulated head versus time (Specific yield = 0.10).

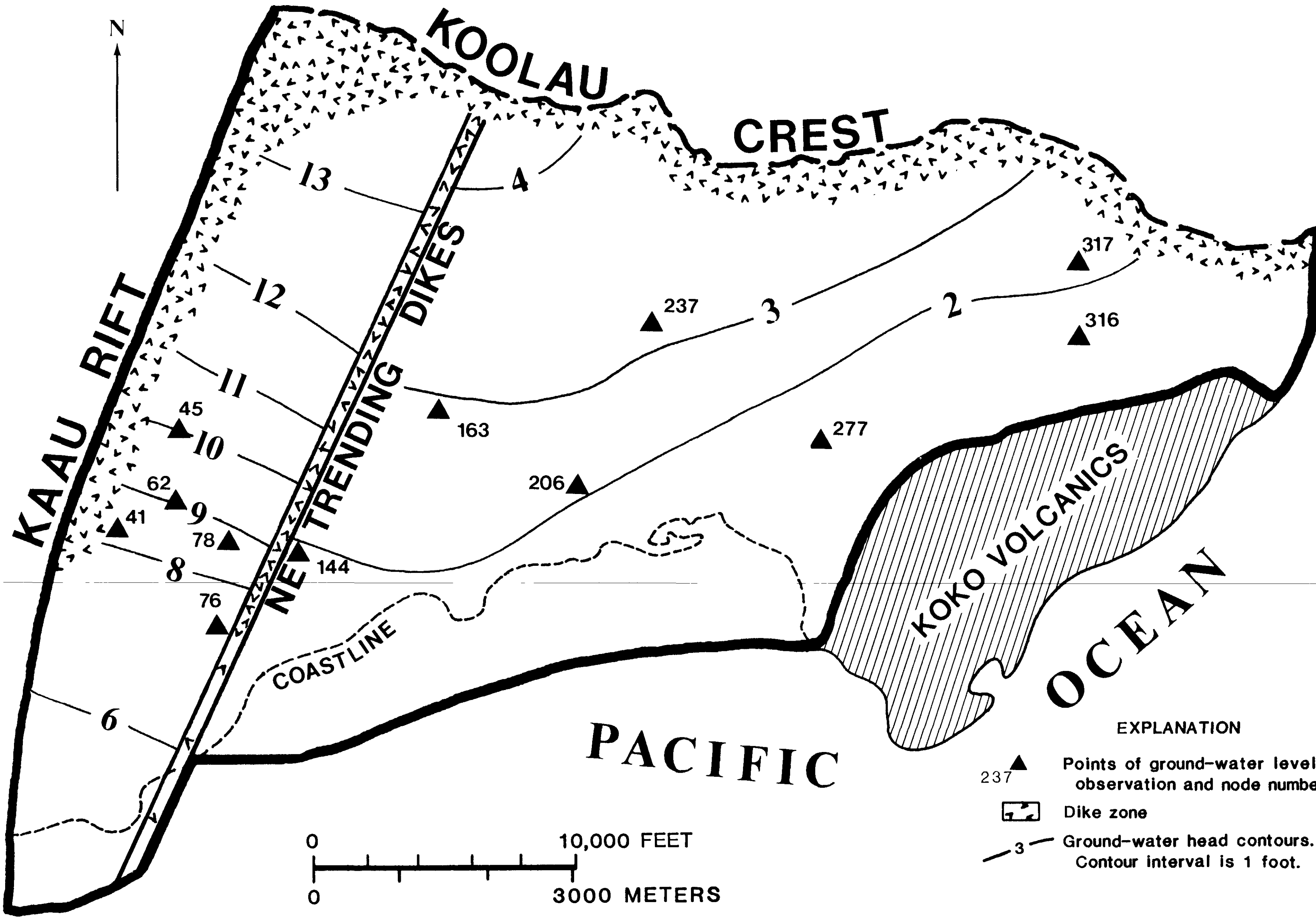


Figure 24. Steady-state head contours resulting from projected pumpage in leeward southeast Oahu.

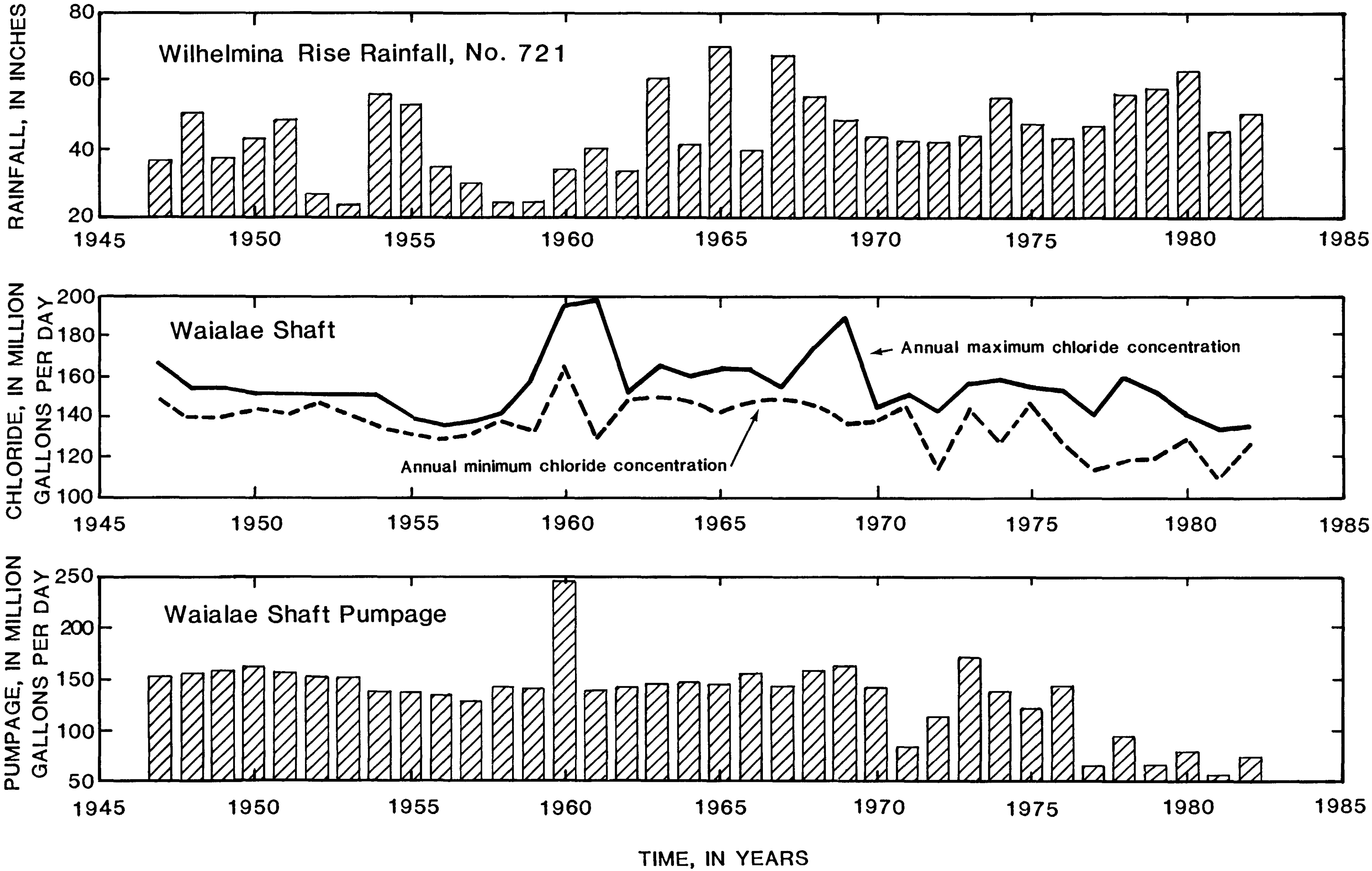


Figure 25. Maximum-minimum chloride concentration and pumpage at Waialae shaft and rainfall at Wilhelmina Rise gage no. 721.

In 1961, the pump at Waialae shaft was shut off for one month, and when pumping was resumed at a relatively low rate of 10 Mgal/mo (million gallons per month), the chloride concentration stabilized at about 150 mg/L.

As rainfall increased through the early- and mid-1960's, pumpage increased slightly with no adverse effect on chloride concentration. The chloride peak of 190 mg/L in 1969 resulted from one month of high pumpage, 22 Mgal/mo. At more moderate rates (12 Mgal/mo) the chloride concentration again stabilized around 150 mg/L, showing seawater upconing as a potential problem that could be avoided with proper management of pumpage.

The computer simulation predicts that with projected pumping rates average future heads will decrease about 1 foot from their present mean position. Such a decrease will make wells in the area somewhat more susceptible to upconing as the lens thickness will decrease to about 85 percent of its 1985 thickness. Available data indicate that chloride concentration at pumped wells probably will not rise more than 100 to 200 mg/L as a result of these new conditions.

SUMMARY

The leeward aquifers of southeast Oahu are bounded by dikes near the crest of the Koolau range to the north, the Kaau rift zone to the west, and the Pacific Ocean to the south and east. Internally, a set of dikes divide the area into the western Waialae area and the eastern Wailupe-Hawaii Kai area. The ground-water flow rate is 6 Mgal/d through the 8.1-mi^2 Waialae area and 9 Mgal/d through the 15.3-mi^2 Wailupe-Hawaii Kai area. Coastal sediments impound the ground water of the Waialae area to an altitude of 10 feet above sea level. This environment is much more advantageous for ground-water development than the Wailupe-Hawaii Kai area, where the head is about three feet and saltwater encroachment is of constant concern. Present pumpage is only 1.2 Mgal/d from the Waialae area and 0.2 Mgal/d from the Wailupe-Hawaii Kai area. Because of the geologic boundaries, increased water development in the study area will not affect the water resources of adjacent aquifers.

The ground-water system was simulated using AQUIFEM-SALT, a two-dimensional finite-element model of ground-water flow for aquifers containing a freshwater-saltwater interface. The model accurately simulates observed heads averaged over several years and predicts an area-wide head decline of about 1 foot when three recently completed wells are put into production.

This drop in head is not enough to cause chloride concentration at pumped wells to rise significantly. However, as in the past, rises in chloride concentration will occur during years of low rainfall or when pumping rates are unusually high.

The magnitude of simulated water table fluctuations, obtained by using annually adjusted recharge data in the AQUIFEM-SALT data set, are in error by a few tenths of a foot relative to observed annual water table fluctuations. This error is caused by inaccuracy in the lens thickness calculated by the Ghyben-Herzberg principle, inaccuracy in the chosen value of specific yield, and by unavoidable inaccuracy in the recharge data. Errors in simulated short term water levels decrease confidence in estimates of the chloride concentration of pumped water.

SUTRA, a solute transport and density dependent flow model developed by Voss (1984b) should be able to produce more detailed simulations of the motion of the lens as well as the distribution of the chloride concentration. Results from this model can be used to improve future AQUIFEM-SALT simulations.

A deep monitor well would provide direct data regarding the location and movement of the interface. Such data would eliminate some ambiguities of the present model, enable changes in pumped water quality to be anticipated, and would also improve the ability of a solute transport model to predict future chloride distributions in the lens.

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SUPPLEMENTAL DATA

Monthly and Annual Average Recharge, by Elements, for Southeast Oahu

Element no.	Recharge in inches: Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Annual recharge	Annual recharge as fraction of annual rainfall	Area in thousands of $feet^2$	Annual recharge in Mgal/d
1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	9,305	0.000
2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	8,360	0.000
3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	1,370	0.000
4	0.8	0.9	0.6	0.6	0.2	0.1	0.1	0.2	0.2	0.3	0.7	0.9	5.7	0.18	900	0.009
5	0.8	0.9	0.6	0.6	0.2	0.1	0.1	0.2	0.2	0.3	0.7	0.9	5.7	0.18	995	0.010
6	0.9	0.9	0.7	0.6	0.3	0.2	0.2	0.2	0.3	0.4	0.8	1.0	6.5	0.18	1,725	0.019
7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	1,040	0.000
8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	750	0.000
9	0.8	0.9	0.6	0.6	0.2	0.1	0.1	0.2	0.2	0.3	0.7	0.9	5.7	0.18	825	0.008
10	0.8	0.9	0.6	0.6	0.2	0.1	0.1	0.2	0.2	0.3	0.7	0.9	5.7	0.18	865	0.008
11	0.9	0.9	0.7	0.6	0.3	0.2	0.2	0.2	0.3	0.4	0.8	1.0	6.5	0.18	1,200	0.013
12	0.9	0.9	0.7	0.6	0.3	0.2	0.2	0.2	0.3	0.4	0.8	1.0	6.5	0.18	1,855	0.021
13	1.0	1.0	0.8	0.7	0.3	0.3	0.3	0.3	0.4	0.4	0.8	1.1	7.4	0.19	2,785	0.035
14	3.9	3.0	2.1	1.9	0.4	0.1	0.0	0.3	0.6	0.8	2.4	3.2	18.8	0.48	3,310	0.106
15	1.2	1.1	0.9	0.9	0.5	0.5	0.4	0.5	0.6	0.6	1.0	1.2	9.6	0.19	4,880	0.080
16	5.2	1.9	0.5	0.5	0.0	0.0	0.0	0.0	0.0	0.0	1.0	2.0	11.2	0.19	4,795	0.092
17	6.5	3.6	3.0	3.2	1.5	1.2	1.2	1.6	1.7	1.6	3.6	4.3	32.8	0.42	4,820	0.270
18	8.4	4.7	3.9	4.3	2.6	2.4	2.3	2.9	2.8	2.5	4.8	5.4	47.0	0.40	4,180	0.335
19	8.4	4.7	3.9	4.3	2.6	2.4	2.3	2.9	2.8	2.5	4.8	5.4	47.0	0.40	4,190	0.336
20	8.1	4.9	3.8	4.0	2.3	2.1	2.0	2.5	2.4	2.2	4.4	5.6	44.3	0.40	3,225	0.244
21	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	8,370	0.000
22	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	9,985	0.000
23	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	1,400	0.000
24	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	1,065	0.000
25	0.8	0.9	0.6	0.6	0.2	0.1	0.1	0.2	0.2	0.3	0.7	0.9	5.7	0.18	1,020	0.010
26	0.8	0.9	0.6	0.6	0.2	0.1	0.1	0.2	0.2	0.3	0.7	0.9	5.7	0.18	865	0.008
27	0.9	0.9	0.7	0.6	0.3	0.2	0.2	0.2	0.3	0.4	0.8	1.0	6.5	0.18	1,020	0.011
28	0.9	0.9	0.7	0.6	0.3	0.2	0.2	0.2	0.3	0.4	0.8	1.0	6.5	0.18	1,770	0.020
29	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	1,410	0.000
30	0.8	0.9	0.6	0.6	0.2	0.1	0.1	0.2	0.2	0.3	0.7	0.9	5.7	0.18	1,000	0.010
31	0.8	0.9	0.6	0.6	0.2	0.1	0.1	0.2	0.2	0.3	0.7	0.9	5.7	0.18	995	0.010
32	0.9	0.9	0.7	0.6	0.3	0.2	0.2	0.2	0.3	0.4	0.8	1.0	6.5	0.18	1,840	0.020
33	3.9	1.6	0.7	0.5	0.0	0.0	0.0	0.0	0.0	0.0	1.0	1.8	9.6	0.24	2,800	0.046
34	3.9	1.6	0.7	0.5	0.0	0.0	0.0	0.0	0.0	0.0	1.0	1.8	9.6	0.24	3,085	0.051
35	4.4	3.4	2.6	2.4	0.9	0.6	0.5	0.9	1.1	1.2	2.9	3.7	24.6	0.52	4,260	0.179
36	5.2	2.0	1.2	1.2	0.0	0.0	0.0	0.0	0.0	0.0	1.7	2.4	13.8	0.23	4,460	0.105
37	6.5	3.3	2.3	2.5	0.8	0.5	0.5	0.9	1.0	0.9	2.9	3.7	25.6	0.33	5,145	0.225
38	8.3	4.5	3.5	4.0	2.2	2.0	2.0	2.5	2.4	2.2	4.4	5.3	43.3	0.38	5,130	0.379
39	8.1	4.4	3.6	4.0	2.3	2.1	2.0	2.5	2.4	2.2	4.4	5.1	43.1	0.39	5,055	0.372
40	7.9	4.8	3.6	3.8	2.1	1.9	1.8	2.3	2.3	2.1	4.3	5.4	42.4	0.40	3,320	0.240
41	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	4,800	0.000
42	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	4,350	0.000
43	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	1,585	0.000
44	0.8	0.9	0.6	0.6	0.2	0.1	0.1	0.2	0.2	0.3	0.7	0.9	5.7	0.18	1,185	0.012

Monthly and Annual Average Recharge, by Elements, for Southeast Oahu

Element no.	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Annual recharge	Annual recharge as fraction of annual rainfall	Area in thousands of feet^2	Annual recharge in Mgal/d
	Recharge in inches															
45	0.8	0.9	0.6	0.6	0.2	0.1	0.1	0.2	0.2	0.3	0.7	0.9	5.7	0.18	1,085	0.011
46	3.5	2.7	1.8	1.6	0.1	0.0	0.0	0.0	0.3	0.5	2.0	2.8	15.3	0.43	2,540	0.066
47	3.7	1.9	1.0	0.7	0.0	0.0	0.0	0.0	0.0	0.0	1.2	2.0	10.5	0.28	1,520	0.027
48	3.9	2.0	1.1	0.9	0.0	0.0	0.0	0.0	0.0	0.0	1.4	2.2	11.6	0.29	1,650	0.033
49	3.9	1.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	1.2	6.7	0.17	2,300	0.026
50	5.2	2.0	1.2	1.2	0.0	0.0	0.0	0.0	0.0	0.0	1.7	2.4	13.8	0.23	2,520	0.059
51	6.5	3.3	2.3	2.5	0.8	0.5	0.5	0.9	1.0	0.9	2.9	3.7	25.6	0.33	2,625	0.115
52	7.7	4.2	3.3	3.7	1.9	1.7	1.6	2.1	2.1	2.0	4.1	4.8	39.3	0.38	2,755	0.185
53	7.6	4.1	3.2	3.5	1.8	1.5	1.5	2.0	1.9	1.8	3.9	4.6	37.3	0.38	3,065	0.195
54	7.4	4.4	3.2	3.3	1.6	1.4	1.3	1.8	1.8	1.7	3.8	5.0	36.5	0.39	1,015	0.063
55	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	4,850	0.000
56	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	5,740	0.000
57	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	1,745	0.000
58	0.8	0.9	0.6	0.6	0.2	0.1	0.1	0.2	0.2	0.3	0.7	0.9	5.7	0.18	1,950	0.019
59	0.8	0.9	0.6	0.6	0.2	0.1	0.1	0.2	0.2	0.3	0.7	0.9	5.7	0.18	1,300	0.013
60	3.3	1.5	0.6	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.8	1.6	8.1	0.26	2,425	0.034
61	3.5	1.7	0.8	0.6	0.0	0.0	0.0	0.0	0.0	0.0	1.0	1.8	9.5	0.27	1,705	0.028
62	3.9	3.0	2.1	1.9	0.4	0.1	0.0	0.3	0.6	0.8	2.4	3.2	18.8	0.48	1,800	0.058
63	3.9	3.0	2.1	1.9	0.4	0.1	0.0	0.3	0.6	0.8	2.4	3.2	18.8	0.48	2,400	0.077
64	5.2	2.1	1.2	1.2	0.0	0.0	0.0	0.0	0.0	0.0	1.7	2.4	13.9	0.24	2,520	0.060
65	6.5	3.3	2.3	2.5	0.8	0.5	0.5	0.9	1.0	0.9	2.9	3.7	25.6	0.33	2,965	0.130
66	7.1	3.7	2.8	3.1	1.4	1.1	1.1	1.5	1.5	1.4	3.5	4.2	32.4	0.36	2,395	0.132
67	6.9	3.6	2.6	2.9	1.2	1.0	0.9	1.3	1.4	1.3	3.3	4.1	30.5	0.35	2,185	0.114
68	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	5,380	0.000
69	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	4,950	0.000
70	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	930	0.000
71	3.3	2.5	1.6	1.3	0.0	0.0	0.0	0.0	0.0	0.3	1.8	2.6	13.4	0.43	2,630	0.060
72	0.8	0.9	0.6	0.6	0.2	0.1	0.1	0.2	0.2	0.3	0.7	0.9	5.7	0.18	2,790	0.027
73	3.5	2.7	1.8	1.6	0.1	0.0	0.0	0.0	0.3	0.5	2.0	2.8	15.3	0.43	5,820	0.152
74	3.5	2.7	1.8	1.6	0.1	0.0	0.0	0.0	0.3	0.5	2.0	2.8	15.3	0.43	3,900	0.102
75	3.9	3.0	2.1	1.9	0.4	0.1	0.0	0.3	0.6	0.8	2.4	3.2	18.8	0.48	4,140	0.133
76	3.9	3.0	2.1	1.9	0.4	0.1	0.0	0.3	0.6	0.8	2.4	3.2	18.8	0.48	5,385	0.173
77	5.0	2.1	1.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	1.4	2.2	12.6	0.23	5,355	0.115
78	6.2	3.1	2.0	2.2	0.5	0.3	0.2	0.6	0.7	0.7	2.6	3.4	22.7	0.30	6,160	0.239
79	6.5	3.3	2.3	2.5	0.8	0.5	0.5	0.9	1.0	0.9	2.9	3.7	25.6	0.33	4,270	0.187
80	6.5	3.3	2.3	2.5	0.8	0.5	0.5	0.9	1.0	0.9	2.9	3.7	25.6	0.33	1,505	0.066
81	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	410	0.000
82	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	585	0.000
83	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	135	0.000
84	3.3	2.5	1.6	1.3	0.0	0.0	0.0	0.0	0.0	0.3	1.8	2.6	13.4	0.43	160	0.004
85	3.3	2.5	1.6	1.3	0.0	0.0	0.0	0.0	0.0	0.3	1.8	2.6	13.4	0.43	120	0.003
86	3.5	1.7	0.8	0.6	0.0	0.0	0.0	0.0	0.0	0.0	1.0	1.8	9.5	0.27	240	0.004
87	3.5	1.7	0.8	0.6	0.0	0.0	0.0	0.0	0.0	0.0	1.0	1.8	9.5	0.27	150	0.002
88	3.9	2.0	1.1	0.9	0.0	0.0	0.0	0.0	0.0	0.0	1.4	2.2	11.6	0.29	160	0.003

Monthly and Annual Average Recharge, by Elements, for Southeast Oahu

Element no.	Recharge in inches Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Annual recharge	Annual recharge as fraction of annual rainfall	Area in thousands of feet^2	Annual recharge in Mgal/d
89	3.9	3.0	2.1	1.9	0.4	0.1	0.0	0.3	0.6	0.8	2.4	3.2	18.8	0.48	200	0.006
90	5.0	2.2	1.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	1.4	2.3	12.8	0.23	210	0.005
91	6.2	3.1	2.0	2.2	0.5	0.3	0.2	0.6	0.7	0.7	2.6	3.4	22.7	0.30	260	0.010
92	6.2	3.1	2.0	2.2	0.5	0.3	0.2	0.6	0.7	0.7	2.6	3.4	22.7	0.30	200	0.008
93	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	875	0.000
94	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	815	0.000
95	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	220	0.000
96	3.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.3	0.10	320	0.002
97	3.3	2.5	1.6	1.3	0.0	0.0	0.0	0.0	0.0	0.3	1.8	2.6	13.4	0.43	240	0.005
98	3.5	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.7	0.10	480	0.003
99	3.5	1.7	0.8	0.6	0.0	0.0	0.0	0.0	0.0	0.0	1.0	1.8	9.5	0.27	300	0.005
100	3.9	2.0	1.1	0.9	0.0	0.0	0.0	0.0	0.0	0.0	1.4	2.2	11.6	0.29	280	0.006
101	4.2	3.2	2.3	2.2	0.6	0.4	0.3	0.6	0.8	1.0	2.7	3.4	21.7	0.50	335	0.012
102	5.0	2.2	1.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	1.4	2.3	12.8	0.23	420	0.009
103	6.1	3.0	1.9	2.0	0.4	0.1	0.0	0.4	0.5	0.6	2.5	3.3	20.8	0.29	455	0.016
104	6.2	3.1	2.0	2.2	0.5	0.3	0.2	0.6	0.7	0.7	2.6	3.4	22.7	0.30	380	0.015
105	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	380	0.000
106	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	460	0.000
107	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	110	0.000
108	0.8	0.9	0.6	0.6	0.2	0.1	0.1	0.2	0.2	0.3	0.7	0.9	5.7	0.18	160	0.002
109	3.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.3	0.10	120	0.001
110	3.5	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.7	0.10	240	0.002
111	3.5	1.7	0.8	0.6	0.0	0.0	0.0	0.0	0.0	0.0	1.0	1.8	9.5	0.27	150	0.002
112	3.9	2.5	1.6	1.4	0.0	0.0	0.0	0.0	0.1	0.3	1.9	2.7	14.4	0.37	170	0.004
113	3.9	2.0	1.1	0.9	0.0	0.0	0.0	0.0	0.0	0.0	1.4	2.2	11.6	0.29	190	0.004
114	5.0	2.2	1.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	1.4	2.3	12.8	0.23	210	0.005
115	6.1	3.0	1.9	2.0	0.4	0.1	0.0	0.4	0.5	0.6	2.5	3.3	20.8	0.29	270	0.010
116	6.1	3.0	1.9	2.0	0.4	0.1	0.0	0.4	0.5	0.6	2.5	3.3	20.8	0.29	180	0.006
117	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	15,405	0.000
118	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	3,370	0.000
119	0.8	0.9	0.6	0.6	0.2	0.1	0.1	0.2	0.2	0.3	0.7	0.9	5.7	0.18	2,380	0.023
120	3.3	2.5	1.6	1.3	0.0	0.0	0.0	0.0	0.0	0.3	1.8	2.6	13.4	0.43	1,595	0.036
121	3.5	1.5	0.6	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.8	1.6	8.5	0.24	3,910	0.057
122	3.5	2.7	1.8	1.6	0.1	0.0	0.0	0.0	0.3	0.5	2.0	2.8	15.3	0.43	2,310	0.060
123	3.9	0.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	5.3	0.13	2,555	0.023
124	3.9	0.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	5.3	0.13	2,475	0.022
125	5.0	2.2	1.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	1.4	2.3	12.8	0.23	2,260	0.049
126	6.1	3.0	1.9	2.0	0.4	0.1	0.0	0.4	0.5	0.6	2.5	3.3	20.8	0.29	2,450	0.087
127	6.1	3.0	1.9	2.0	0.4	0.1	0.0	0.4	0.5	0.6	2.5	3.3	20.8	0.29	1,195	0.042
128	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	14,495	0.000
129	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	6,070	0.000
130	3.3	2.5	1.6	1.3	0.0	0.0	0.0	0.0	0.0	0.3	1.8	2.6	13.4	0.43	5,350	0.122
131	3.3	2.5	1.6	1.3	0.0	0.0	0.0	0.0	0.0	0.3	1.8	2.6	13.4	0.43	5,360	0.123
132	0.8	0.9	0.6	0.6	0.2	0.1	0.1	0.2	0.2	0.3	0.7	0.9	5.7	0.18	3,780	0.037

Monthly and Annual Average Recharge, by Elements, for Southeast Oahu

Element no.	Recharge in inches												Annual recharge	Annual recharge as fraction of annual rainfall	Area in thousands of $feet^2$	Annual recharge in Mgal/d
	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec				
133	0.9	0.9	0.7	0.6	0.3	0.2	0.2	0.2	0.3	0.4	0.8	1.0	6.5	0.18	3,050	0.034
134	3.9	0.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	5.3	0.13	3,260	0.029
135	4.2	2.2	1.3	1.2	0.0	0.0	0.0	0.0	0.0	0.0	1.7	2.4	13.0	0.30	3,070	0.068
136	5.0	2.2	1.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	1.4	2.3	12.8	0.23	2,810	0.061
137	5.5	2.6	1.5	1.5	0.0	0.0	0.0	0.0	0.1	0.1	1.9	2.8	15.9	0.25	2,475	0.067
138	5.8	2.8	1.7	1.8	0.1	0.0	0.0	0.2	0.3	0.3	2.2	3.0	18.2	0.27	825	0.026
139	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	5,545	0.000
140	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	4,100	0.000
141	0.8	0.9	0.6	0.6	0.2	0.1	0.1	0.2	0.2	0.3	0.7	0.9	5.7	0.18	1,325	0.013
142	0.8	0.9	0.6	0.6	0.2	0.1	0.1	0.2	0.2	0.3	0.7	0.9	5.7	0.18	2,665	0.026
143	0.9	0.9	0.7	0.6	0.3	0.2	0.2	0.2	0.3	0.4	0.8	1.0	6.5	0.18	3,240	0.036
144	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	4,790	0.000
145	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	3,930	0.000
146	0.8	0.9	0.6	0.6	0.2	0.1	0.1	0.2	0.2	0.3	0.7	0.9	5.7	0.18	1,605	0.016
147	0.8	0.9	0.6	0.6	0.2	0.1	0.1	0.2	0.2	0.3	0.7	0.9	5.7	0.18	1,730	0.017
148	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	1,850	0.000
149	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	975	0.000
150	3.3	2.5	1.6	1.3	0.0	0.0	0.0	0.0	0.0	0.3	1.8	2.6	13.4	0.43	1,215	0.028
151	3.3	2.5	1.6	1.3	0.0	0.0	0.0	0.0	0.0	0.3	1.8	2.6	13.4	0.43	2,260	0.052
152	0.9	0.9	0.7	0.6	0.3	0.2	0.2	0.2	0.3	0.4	0.8	1.0	6.5	0.18	4,720	0.052
153	3.5	2.7	1.8	1.6	0.1	0.0	0.0	0.0	0.3	0.5	2.0	2.8	15.3	0.43	2,400	0.063
154	3.9	3.4	2.5	2.3	0.8	0.5	0.4	0.7	1.0	1.2	2.8	3.6	23.2	0.59	2,640	0.105
155	4.2	1.4	0.3	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.7	1.4	8.2	0.19	2,240	0.031
156	5.0	2.2	1.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	1.4	2.3	12.8	0.23	2,265	0.049
157	5.5	2.6	1.5	1.5	0.0	0.0	0.0	0.0	0.1	0.1	1.9	2.8	15.9	0.25	1,875	0.051
158	5.5	2.6	1.5	1.5	0.0	0.0	0.0	0.0	0.1	0.1	1.9	2.8	15.9	0.25	435	0.012
159	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	1,310	0.000
160	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	950	0.000
161	3.3	2.5	1.6	1.3	0.0	0.0	0.0	0.0	0.0	0.3	1.8	2.6	13.4	0.43	1,380	0.032
162	3.3	2.5	1.6	1.3	0.0	0.0	0.0	0.0	0.0	0.3	1.8	2.6	13.4	0.43	2,270	0.052
163	3.5	1.7	0.8	0.6	0.0	0.0	0.0	0.0	0.0	0.0	1.0	1.8	9.5	0.27	5,590	0.091
164	3.5	2.4	1.5	1.3	0.0	0.0	0.0	0.0	0.0	0.2	1.7	2.5	13.2	0.37	3,800	0.086
165	3.9	3.0	2.1	1.9	0.4	0.1	0.0	0.3	0.6	0.8	2.4	3.2	18.8	0.48	3,645	0.117
166	4.4	2.4	1.6	1.4	0.0	0.0	0.0	0.0	0.1	0.2	1.9	2.7	14.7	0.31	2,595	0.065
167	5.0	2.2	1.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	1.4	2.3	12.8	0.23	2,270	0.050
168	5.5	2.6	1.5	1.5	0.0	0.0	0.0	0.0	0.1	0.1	1.9	2.8	15.9	0.25	1,585	0.043
169	5.5	2.6	1.5	1.5	0.0	0.0	0.0	0.0	0.1	0.1	1.9	2.8	15.9	0.25	180	0.005
170	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	2,945	0.000
171	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	2,205	0.000
172	0.8	0.9	0.6	0.6	0.2	0.1	0.1	0.2	0.2	0.3	0.7	0.9	5.7	0.18	990	0.010
173	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	2,440	0.000
174	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	1,900	0.000
175	0.8	0.9	0.6	0.6	0.2	0.1	0.1	0.2	0.2	0.3	0.7	0.9	5.7	0.18	1,210	0.012
176	0.8	0.9	0.6	0.6	0.2	0.1	0.1	0.2	0.2	0.3	0.7	0.9	5.7	0.18	1,300	0.013

Element no.	Recharge in inches Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Annual recharge	Annual recharge as fraction of annual rainfall	Area in thousands of feet^2	Annual recharge in Mgal/d
177	3.5	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.9	0.11	3,705	0.025
178	3.5	0.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.9	5.4	0.15	4,040	0.037
179	3.9	1.6	0.7	0.5	0.0	0.0	0.0	0.0	0.0	0.0	1.0	1.8	9.6	0.24	3,465	0.057
180	4.7	2.1	1.3	1.2	0.0	0.0	0.0	0.0	0.0	0.0	1.7	2.4	13.4	0.26	2,355	0.054
181	5.0	2.2	1.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	1.4	2.3	12.8	0.23	2,490	0.054
182	5.2	2.4	1.2	1.2	0.0	0.0	0.0	0.0	0.0	0.0	1.7	2.5	14.3	0.24	1,545	0.038
183	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	2,235	0.000
184	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	1,225	0.000
185	0.8	0.9	0.6	0.6	0.2	0.1	0.1	0.2	0.2	0.3	0.7	0.9	5.7	0.18	760	0.007
186	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	2,420	0.000
187	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	1,180	0.000
188	0.8	0.9	0.6	0.6	0.2	0.1	0.1	0.2	0.2	0.3	0.7	0.9	5.7	0.18	1,050	0.010
189	0.8	0.9	0.6	0.6	0.2	0.1	0.1	0.2	0.2	0.3	0.7	0.9	5.7	0.18	875	0.009
190	3.5	2.7	1.8	1.6	0.1	0.0	0.0	0.0	0.3	0.5	2.0	2.8	15.3	0.43	4,300	0.112
191	3.9	1.6	0.7	0.5	0.0	0.0	0.0	0.0	0.0	0.0	1.0	1.8	9.6	0.24	4,275	0.070
192	4.2	3.2	2.3	2.2	0.6	0.4	0.3	0.6	0.8	1.0	2.7	3.4	21.7	0.50	3,915	0.145
193	4.7	2.0	0.8	0.7	0.0	0.0	0.0	0.0	0.0	0.0	1.2	2.0	11.4	0.22	2,665	0.052
194	5.0	2.2	1.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	1.4	2.3	12.8	0.23	2,650	0.058
195	5.2	2.4	1.2	1.2	0.0	0.0	0.0	0.0	0.0	0.0	1.7	2.5	14.3	0.24	750	0.018
196	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	5,280	0.000
197	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	2,730	0.000
198	3.3	2.5	1.6	1.3	0.0	0.0	0.0	0.0	0.0	0.3	1.8	2.6	13.4	0.43	3,595	0.082
199	3.3	2.0	1.1	0.8	0.0	0.0	0.0	0.0	0.0	0.0	1.3	2.1	10.6	0.34	2,810	0.051
200	3.5	1.3	0.4	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.6	1.4	7.5	0.21	5,520	0.071
201	3.9	3.0	2.1	1.9	0.4	0.1	0.0	0.3	0.6	0.8	2.4	3.2	18.8	0.48	2,775	0.089
202	4.4	3.4	2.6	2.4	0.9	0.6	0.5	0.9	1.1	1.2	2.9	3.7	24.6	0.52	2,365	0.099
203	4.7	2.0	0.8	0.7	0.0	0.0	0.0	0.0	0.0	0.0	1.2	2.0	11.4	0.22	2,140	0.042
204	5.0	2.2	1.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	1.4	2.3	12.8	0.23	2,330	0.051
205	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	3,925	0.000
206	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	2,560	0.000
207	0.8	0.9	0.6	0.6	0.2	0.1	0.1	0.2	0.2	0.3	0.7	0.9	5.7	0.18	1,175	0.011
208	0.5	0.6	0.4	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.6	2.7	0.17	1,125	0.005
209	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	4,190	0.000
210	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	2,565	0.000
211	0.8	0.9	0.6	0.6	0.2	0.1	0.1	0.2	0.2	0.3	0.7	0.9	5.7	0.18	880	0.009
212	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	3,705	0.000
213	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	2,660	0.000
214	3.5	2.0	1.1	0.9	0.0	0.0	0.0	0.0	0.0	0.0	1.3	2.1	11.0	0.31	2,480	0.047
215	3.5	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.2	0.12	4,425	0.032
216	3.9	3.0	2.1	1.9	0.4	0.1	0.0	0.3	0.6	0.8	2.4	3.2	18.8	0.48	6,400	0.205
217	4.2	3.2	2.3	2.2	0.6	0.4	0.3	0.6	0.8	1.0	2.7	3.4	21.7	0.50	5,380	0.199
218	4.7	2.6	1.8	1.7	0.1	0.0	0.0	0.1	0.3	0.5	2.2	2.9	16.9	0.33	4,130	0.119
219	5.0	2.2	1.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	1.4	2.3	12.8	0.23	5,070	0.111
220	5.0	2.2	1.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	1.4	2.3	12.8	0.23	1,215	0.027

Monthly and Annual Average Recharge, by Elements, for Southeast Oahu

Element no.	Recharge in inches Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Annual recharge	Annual recharge as fraction of annual rainfall	Area in thousands of feet^2	Annual recharge in Mgal/d
221	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	5,320	0.000
222	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	2,160	0.000
223	0.9	0.9	0.7	0.6	0.3	0.2	0.2	0.2	0.3	0.4	0.8	1.0	6.5	0.18	875	0.010
224	3.5	2.7	1.8	1.6	0.1	0.0	0.0	0.0	0.3	0.5	2.0	2.8	15.3	0.43	1,480	0.039
225	3.9	3.0	2.1	1.9	0.4	0.1	0.0	0.3	0.6	0.8	2.4	3.2	18.8	0.48	2,360	0.076
226	4.7	2.6	1.8	1.7	0.1	0.0	0.0	0.1	0.3	0.5	2.2	2.9	16.9	0.33	3,330	0.096
227	4.7	2.0	0.8	0.7	0.0	0.0	0.0	0.0	0.0	0.0	1.2	2.0	11.4	0.22	1,100	0.021
228	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	4,700	0.000
229	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	1,775	0.000
230	3.5	1.6	0.7	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.9	1.7	9.0	0.25	2,710	0.042
231	3.5	2.7	1.8	1.6	0.1	0.0	0.0	0.0	0.3	0.5	2.0	2.8	15.3	0.43	2,650	0.069
232	3.9	3.0	2.1	1.9	0.4	0.1	0.0	0.3	0.6	0.8	2.4	3.2	18.8	0.48	3,180	0.102
233	4.7	2.6	1.8	1.7	0.1	0.0	0.0	0.1	0.3	0.5	2.2	2.9	16.9	0.33	2,615	0.075
234	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	4,350	0.000
235	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	1,965	0.000
236	0.9	0.9	0.7	0.6	0.3	0.2	0.2	0.2	0.3	0.4	0.8	1.0	6.5	0.18	2,050	0.023
237	1.0	1.0	0.8	0.7	0.3	0.3	0.3	0.3	0.4	0.4	0.8	1.1	7.4	0.19	1,270	0.016
238	3.9	1.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	1.2	6.7	0.17	1,335	0.015
239	4.2	3.8	2.9	2.8	1.2	1.0	0.9	1.2	1.4	1.6	3.3	4.0	28.3	0.65	3,525	0.170
240	4.4	4.0	3.2	3.0	1.5	1.2	1.1	1.5	1.7	1.8	3.5	4.3	31.2	0.66	3,330	0.177
241	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	4,055	0.000
242	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	2,275	0.000
243	0.9	0.9	0.7	0.6	0.3	0.2	0.2	0.2	0.3	0.4	0.8	1.0	6.5	0.18	1,895	0.021
244	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	2,300	0.000
245	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	1,625	0.000
246	3.5	2.7	1.8	1.6	0.1	0.0	0.0	0.0	0.3	0.5	2.0	2.8	15.3	0.43	6,105	0.159
247	3.9	3.0	2.1	1.9	0.4	0.1	0.0	0.3	0.6	0.8	2.4	3.2	18.8	0.48	3,340	0.107
248	4.2	3.2	2.3	2.2	0.6	0.4	0.3	0.6	0.8	1.0	2.7	3.4	21.7	0.50	3,645	0.135
249	4.4	3.4	2.6	2.4	0.9	0.6	0.5	0.9	1.1	1.2	2.9	3.7	24.6	0.52	3,995	0.168
250	4.4	4.0	3.2	3.0	1.5	1.2	1.1	1.5	1.7	1.8	3.5	4.3	31.2	0.66	1,600	0.085
251	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	2,525	0.000
252	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	3,450	0.000
253	3.9	3.0	2.1	1.9	0.4	0.1	0.0	0.3	0.6	0.8	2.4	3.2	18.8	0.48	8,000	0.257
254	3.9	3.0	2.1	1.9	0.4	0.1	0.0	0.3	0.6	0.8	2.4	3.2	18.8	0.48	4,140	0.133
255	4.2	3.8	2.9	2.8	1.2	1.0	0.9	1.2	1.4	1.6	3.3	4.0	28.3	0.65	3,960	0.191
256	4.4	4.0	3.2	3.0	1.5	1.2	1.1	1.5	1.7	1.8	3.5	4.3	31.2	0.66	1,395	0.074
257	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	2,625	0.000
258	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	3,590	0.000
259	1.0	1.0	0.8	0.7	0.3	0.3	0.3	0.3	0.4	0.4	0.8	1.1	7.4	0.19	4,645	0.059
260	3.9	3.0	2.1	1.9	0.4	0.1	0.0	0.3	0.6	0.8	2.4	3.2	18.8	0.48	3,045	0.098
261	4.2	3.2	2.3	2.2	0.6	0.4	0.3	0.6	0.8	1.0	2.7	3.4	21.7	0.50	4,260	0.158
262	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	1,190	0.000
263	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	1,935	0.000
264	3.9	3.0	2.1	1.9	0.4	0.1	0.0	0.3	0.6	0.8	2.4	3.2	18.8	0.48	6,730	0.216

Monthly and Annual Average Recharge, by Elements, for Southeast Oahu

Element no.	Recharge in inches Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Annual recharge	Annual recharge as fraction of annual rainfall	Area in thousands of $feet^2$	Annual recharge in Mgal/d
265	3.9	3.0	2.1	1.9	0.4	0.1	0.0	0.3	0.6	0.8	2.4	3.2	18.8	0.48	9,220	0.296
266	4.2	3.8	2.9	2.8	1.2	1.0	0.9	1.2	1.4	1.6	3.3	4.0	28.3	0.65	3,285	0.159
267	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	1,190	0.000
268	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	2,800	0.000
269	1.0	1.0	0.8	0.7	0.3	0.3	0.3	0.3	0.4	0.4	0.8	1.1	7.4	0.19	5,235	0.066
270	3.9	3.0	2.1	1.9	0.4	0.1	0.0	0.3	0.6	0.8	2.4	3.2	18.8	0.48	7,460	0.239
271	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	5,705	0.000
272	3.9	3.0	2.1	1.9	0.4	0.1	0.0	0.3	0.6	0.8	2.4	3.2	18.8	0.48	11,225	0.360
273	3.9	3.0	2.1	1.9	0.4	0.1	0.0	0.3	0.6	0.8	2.4	3.2	18.8	0.48	10,635	0.341
274	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	3,070	0.000
275	0.9	0.9	0.7	0.6	0.3	0.2	0.2	0.2	0.3	0.4	0.8	1.0	6.5	0.18	2,725	0.030
276	3.9	1.1	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	1.3	7.1	0.18	3,985	0.048
277	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	2,175	0.000
278	3.3	2.5	1.6	1.3	0.0	0.0	0.0	0.0	0.0	0.3	1.8	2.6	13.4	0.43	9,270	0.212
279	3.5	2.7	1.8	1.6	0.1	0.0	0.0	0.0	0.3	0.5	2.0	2.8	15.3	0.43	9,900	0.258
280	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	3,115	0.000
281	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	3,045	0.000
282	2.9	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	3.6	0.13	7,140	0.044
283	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	1,135	0.000
284	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	3,060	0.000
														TOTALS	804,080	15.063